PB81-248163

Engineering Handbook for Hazardous Waste Incineration

Monsanto Research Corp.
Dayton, OH

Prepared for

Environmental Protection Agency
Washington, DC

Sep 81

U.S. Department of Commerce
National Technical Information Service
NTIS

SW-889

PB81-248163

ENGINEERING HANDBOOK FOR HAZARDOUS WASTE INCINERATION

June 1981

by

T. A. Bonner, C. L. Cornett, B. O. Desai, J. M. Fullenkamp, T. W. Hughes
M. L. Johnson, E. D. Kennedy, R. J. McCormick, J. A. Peters and D. L. Zanders

Monsanto Research Corporation
1515 Nicholas Road
Dayton, Ohio 45407

EPA Contract No. 68-03-3025; Work Directive SDM02

Project Officer: Mr. Donald A. Oberacker

Industrial Environmental Research Laboratory
Office of Environmental Engineering and Technology
Cincinnati, Ohio 45208

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

487

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. SW-889	**2.**	**3. RECIPIENT'S ACCESSION NO.** PB81 248163
4. TITLE AND SUBTITLE Engineering Handbook for Hazardous Waste Incineration		**5. REPORT DATE** September 1981 **6. PERFORMING ORGANIZATION CODE**
7. AUTHOR(S) T. A. Bonner, C. L. Cornett, B. O. Desai, J. M. Fullenkamp, T. W. Hughes, M. L. Johnson, E. D. Kennedy, R. J. McCormick, J. A. Peters and D. L. Zanders		**8. PERFORMING ORGANIZATION REPORT NO.** MRC-DA 1090
9. PERFORMING ORGANIZATION NAME AND ADDRESS Monsanto Research Corporation 1515 Nicholas Road Dayton, Ohio 45418		**10. PROGRAM ELEMENT NO.** **11. CONTRACT/GRANT NO.** 68-03-3025; SCM02
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency Office of Solid Waste 401 M Street, S.W. Washington, D.C. 20460		**13. TYPE OF REPORT AND PERIOD COVERED** Final, Mar. 1981 to Sept. 1981 **14. SPONSORING AGENCY CODE** ----

15. SUPPLEMENTARY NOTES

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16. ABSTRACT

The Resource Conservation and Recovery Act (RCRA) authorizes the United States Environmental Protection Agency (EPA) to regulate owners/operators of facilities that treat hazardous waste in incinerators. Pursuant to the legislative mandates specified in RCRA, the EPA has proposed regulations to ensure that hazardous waste incinerators are operated in an environmentally responsible manner. Specifically, the proposed regulations include an operational performance standard, general design and construction requirements, combustion and destruction criteria, waste analysis, trial burns, monitoring and inspections, recordkeeping and reporting, emission control criteria, control of fugitive emissions, and closure.

The proposed regulations rely upon the technical advisory information contained in this document - Engineering Handbook for Hazardous Waste Incineration. The proposed regulations provide very little specificity pertaining to actual hazardous waste incineration performance requirements. Permitting officials will develop best engineering judgments for each site based primarily on suggested minimums or acceptable ranges for performance parameters contained in this report. As a result, each permitting official will set a "standard" for each hazardous waste incineration facility based on the application of the criteria or factors contained in the proposed regulations and this document.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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18. DISTRIBUTION STATEMENT Unlimited	**19. SECURITY CLASS** *(This Report)* Unclassified	**21. NO. OF PAGES** 487
	20. SECURITY CLASS *(This page)* Unclassified	**22. PRICE**

EPA Form 2220-1 (9-73)

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PREFACE

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CHAPTER 1

INTRODUCTION

Millions of tons of industrial waste materials are generated each year in the United States. A sizable fraction of this waste is considered hazardous (an estimated 57 million metric tons in 1980). In recent years, incineration has emerged as an attractive potential alternative to hazardous waste disposal methods such as landfill, ocean dumping, and deep-well injection.

Incineration possesses several advantages as a hazardous waste disposal technology:

- Toxic components of hazardous wastes can be converted to harmless compounds or, at least, to less harmful compounds.
- Incineration provides for the ultimate disposal of hazardous wastes, eliminating the possibility of problems resurfacing in the future.
- The volume of hazardous waste is greatly reduced by incineration.
- Heat recovery makes it possible to recover some of the energy produced by the combustion process.

It is likely that incineration will be a principal technology for the disposal of hazardous waste in the future because of the above advantages.

This engineering handbook is a compilation of information available in the literature and describes current state-of-the-art technology for the incineration of hazardous waste. The handbook is designed to serve as a technical resource document in the evaluation of hazardous waste incineration operations. This document is intended to serve as a useful technical resource for Federal, regional, and state EPA officials; designers of hazardous waste incineration facilities, owners and operators of hazardous waste incineration facilities, and the general technical community.

Each chapter in the handbook addresses a separate topic involved in hazardous waste incineration. A brief abstract for each chapter is presented in Table 1-1.

The user is encouraged to make use of the references cited in each chapter if additional information is required.

TABLE 1-1. ENGINEERING HANDBOOK FOR HAZARDOUS WASTE INCINERATION - CHAPTERS AND THEIR CONTENT

Chapter	Abstract
1	Introduction Describes the utility of the handbook and its structure, specifying where various types of information are available.
2	Current Practices Provides an overview of incineration systems for various types of waste. Commercially available technology, emerging technology, and foreign technology are included. The components of these systems are described in detail, including air pollution control devices and heat recovery systems. A matrix of the types of components applicable to different generic types of waste is provided, along with a list of U.S. incinerator manufacturers.
3	Waste Characterization Describes the basic types of analysis required to characterize wastes, and discusses how the resulting data are used to match a waste to an appropriate type of incinerator. Hazardous wastes listed under Section 3001 of the RCRA regulations are evaluated for their suitability for incineration.
4	Incinerator and Air Pollution Control System Design Evaluation Provides detailed information and procedures for evaluation of incinerator and air pollution control device design and operating conditions. Basically, this involves a series of internal consistency checks designed to determine whether (1) acceptable temperatures, residence times, oxygen concentrations, and mixing can be achieved and maintained in the incinerator, (2) the various components of the system have sufficient capacity to accommodate the quantities of waste to be burned, (3) appropriate air pollution control device operating conditions can be maintained, (4) the design includes process control and automatic shutdown safeguards to minimize release of hazardous materials in the event of equipment malfunction, and (5) proper materials of construction are used. Individual evaluation procedures are provided for liquid injection and rotary kiln incinerators, and for several types of wet scrubbers.

(continued)

TABLE 1-1 (continued)

Chapter	Abstract
5	Overall Facility Design, Operation, and Monitoring Provides engineering background information on the technical capabilities necessary for the incineration facility to process hazardous waste safely and effectively. The chapter discusses overall facility layouts; equipment requirements common to all facilities; waste receiving equipment, procedures, and storage; personnel safety; emergency procedures and provisions; monitoring procedures and instrumentation; sampling and analysis equipment and methodologies; sources of fugitive emissions and their control; scrubber/quench water handling and disposal; and ash collection systems.
6	Estimating Incineration Costs Examines the economic factors involved in the construction of new facilities and the operation of existing facilities. Capital costs for incinerators and air pollution control devices are discussed. The costs involved in changing incinerator operating conditions (temperature, percent excess air, residence time) and the removal efficiency of air pollution control devices are examined. The costs involved in performing trial burns are also addressed in this chapter.
Appendices	Provide a subject index, glossary of terms, tables of conversion factors, bibliography, and descriptions of equipment used for laboratory-scale thermal chemical waste decomposition experiments. The results of laboratory experiments and trial burn studies are also summarized.

CHAPTER 2

CURRENT PRACTICES

2.1 INTRODUCTION

Incineration has developed over a number of years as a means for disposal of a wide variety of waste materials. Recently, applying incineration to hazardous waste disposal has been given an increasing amount of attention as an alternative to more expensive and controversial treatment and disposal technologies. Besides the economics involved, another advantage of incineration is that it does not necessarily need to be carried out at land-based facilities. Shipboard incineration is currently being studied and utilized in destruction of dangerous chlorinated hydrocarbon wastes [1, 2].

The U.S. Environmental Protection Agency estimates that in 1979 only 5% of the country's total hazardous waste stream was managed by incineration, yet 60% of the total wastes could have been successfully destroyed using current incinerator technology [1, 2].

The EPA estimates further that in 1979 about 39 million short tons (35 million metric tons) of hazardous wastes were generated in this country by some 270,000 industrial plants and other facilities. The majority of these wastes (65%) were produced in ten states: Texas, Ohio, Pennsylvania, Louisiana, Michigan, Indiana, Illinois, Tennessee, West Virginia, and California. It is expected that the quantities of hazardous waste generated will increase annually by 3%. Based on these figures, incineration is becoming an increasingly more important option in solving hazardous waste disposal problems [3, 4].

Incineration is an engineered process using thermal oxidation of a waste material to produce a less bulky, toxic, or noxious material. A waste must be combustible to some extent in order for incineration to be a viable disposal method [5]. The 3 T's of combustion, temperature, residence time, and turbulence, are crucial in controlling operating conditions. Table 2-1 summarizes the typical ranges for temperature and residence time in six incineration processes. Chapter 4 deals with turbulence and oxygen availability.

The waste characteristics are likewise important parameters, including chemical structure and physical form. Table 2-2 presents a summary of those physical forms suitable for each of the six types of incinerators. Table 2-3 lists candidate compounds for destruction by incineration.

This chapter outlines the basic variations of incinerator processes and illustrates the individual components and their applications. Included are six types of incinerator technologies, along with pertinent air pollution control

TABLE 2-1. PERTINENT INCINERATION PROCESSES AND THEIR TYPICAL OPERATING RANGES [6]

Process	Temperature range, °F (°C)	Residence time
Rotary kiln[a]	1,500 to 2,900 (820 to 1,600)	Liquids and gases, seconds; solids, hours
Liquid injection[a]	1,200 to 2,900 (650 to 1,600)	0.1 to 2 seconds
Fluidized bed	840 to 1,800 (450 to 980)	Liquids and gases, seconds; solids, longer
Multiple hearth	Drying zone 600 to 1,000 (320 to 540) Incineration 1,400 to 1,800 (760 to 980)	0.25 to 1.5 hours
Coincineration	300 to 2,900 (150 to 1,600)	Seconds to hours
Starved air combustion/pyrolysis	900 to 1,500 (480 to 820)	Tenth of a second to several hours

[a] A highly developed hazardous waste incineration technology; covered in detail in Chapter 4.

TABLE 2-2. APPLICABILITY OF AVAILABLE INCINERATION PROCESSES TO INCINERATION OF HAZARDOUS WASTE BY TYPE [6]

Waste type	Rotary kiln[a]	Liquid injection	Fluidized bed[a]	Multiple hearth	Coincineration	Starved air combustion/ pyrolysis
Solids:						
Granular, homogeneous	X		X	X	X	X
Irregular, bulky (pallets, etc.)	X				X	X[b]
Low melting point (tars, etc.)	X	X[c]	X		X	X
Organic compounds with fusible ash constituents	X			X	X	X
Unprepared, large, bulky material	X					
Gases:						
Organic vapor laden	X[d]	X[d]	X[d]	X[d]	X[d]	X[d]
Liquids:						
High organic strength aqueous wastes, often toxic	X[e]	X	X		X	
Organic liquids	X[e]	X	X		X	
Solids/liquids:						
Waste contains halogenated aromatic compounds (2,200°F minimum)	X	X[f]			X	
Aqueous organic sludges	X[g]		X	X	X	

[a] Suitable for pyrolysis operation.

[b] Handles large material on a limited basis.

[c] If material can be melted and pumped.

[d] If properly presented to the incinerator.

[e] If equipped with auxiliary liquid injection nozzles.

[f] If liquid.

[g] Provided waste does not become sticky upon drying.

TABLE 2-3. WASTE CHEMICAL STREAM CONSTITUENTS WHICH MAY BE SUBJECTED TO ULTIMATE DISPOSAL BY CONTROLLED INCINERATION [7]

ORGANIC

Acetaldehyde
Acetic acid
Acetic anhydride
Acetone
Acetone cyanohydrin: oxides of nitrogen are removed from the effluent gas by scrubbers and/or thermal devices.
Acetonitrile: oxides of nitrogen are removed from the effluent gas by scrubbers and/or thermal devices.
Acetyl chloride
Acetylene
Acridine: oxides of nitrogen are removed from the effluent gas by scrubber, catalytic, or thermal device.
Acrolein: 1500°F, 0.5 sec minimum for primary combustion; 2000°F, 1.0 sec for secondary combustion, combustion products CO_2 and H_2O.
Acrylic acid
Acrylonitrile: NO_x removed from effluent gas by scrubbers and/or thermal devices.
Adipic acid
Allyl alcohol
Allyl chloride: 1800°F, 2 sec minimum.
Aminoethylethanolamine: incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions.
Amyl acetate
Amyl alcohol
Aniline: oxides of nitrogen are removed from the effluent gas by scrubber, catalytic, or thermal device.
Anthracene
Benzene
Benzene sulfonic acid: incineration followed by scrubbing to remove the SO_2 gas.
Benzoic acid
Benzyl chloride: 1500°F, 0.5 sec minimum for primary combustion; 2200°F, 1.0 sec for secondary combustion; elemental chlorine formation may be alleviated through injection of steam or methane into the combustion process.
Butadiene
Butane
Butanols
1-Butene
Butyl acrylate
n-Butylamine: incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions.
Butylenes
Butyl phenol
Butyraldehyde

(continued)

TABLE 2-3 (continued)

Camphor
Carbolic acid (phenol)
Carbon disulfide: a sulfur dioxide scrubber is necessary when combusting significant quantities of carbon disulfide.
Carbon monoxide
Carbon tetrachloride: preferably after mixing with another combustible fuel; care must be exercised to assure complete combustion to prevent the formation of phosgene; an acid scrubber is necessary to remove the halo acids produced.
Chloral hydrate: same as carbon tetrachloride.
Chlorobenzene: same as carbon tetrachloride.
Chloroform: same as carbon tetrachloride.
Creosote
Cresol
Crotonaldehyde
Cumene
Cyanoacetic acid: oxides of nitrogen are removed from the effluent gas by scrubbers and/or thermal devices.
Cyclohexane
Cyclohexanol
Cyclohexanone
Cyclohexylamine: incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions.
Decyl alcohol
Di-n-butyl phthalate
Dichlorobenzene: incineration, preferably after mixing with another combustible fuel; care must be exercised to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.
Dichlorodifluoromethane (freon): same as dichlorobenzene.
Dichloroethyl ether: same as dichlorobenzene.
Dichloromethane: (methylene chloride) same as dichlorobenzene.
1,2-Dichloropropane: same as dichlorobenzene.
Dichlorotetrafluoroethane: same as dichlorobenzene.
Dicyclopentadiene
Diethnolamine: incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions.
Diethylamine: same as diethanolamine.
Diethylene glycol
Diethyl ether: concentrated waste containing no peroxides; discharge liquid at a controlled rate near a pilot flame. Concentrated waste containing peroxides; perforation of a container of the waste from a safe distance followed by open burning.
Diethyl phthalate
Diethylstilbestrol
Diisobutylene
Diisobutyl ketone

(continued)

TABLE 2-3 (continued)

Diisopropanolamine: incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions.
Dimethylamine: same as diisopropanolamine.
Dimethyl sulfate: incineration (1800°F, 1.5 sec minimum) of dilute, neutralized dimethyl sulfate waste is recommended. The incinerator must be equipped with efficient scrubbing devices for oxides of sulfur.
2,4-Dinitroaniline: controlled incineration whereby oxides of nitrogen are removed from the effluent gas by scrubber, catalytic, or thermal device.
Dinitrobenzol: incineration (1800°F, 2.0 sec minimum) followed by removal of the oxides of nitrogen that are formed using scrubbers and/or catalytic or thermal devices. The dilute wastes should be concentrated before incineration.
Dinitrocresol: incineration (1100°F minimum) with adequate scrubbing and ash disposal facilities.
Dinitrophenol: incinerated (1800°F, 2.0 sec minimum) with adequate scrubbing equipment for the removal of NO_x.
Dinitrotoluene: pretreatment involves contact of the dinitrotoluene contaminated waste with $NaHCO_3$ and solid combustibles followed by incineration in an alkaline scrubber equipped incinerator unit.
Dioxane: concentrated waste containing no peroxides; discharge liquid at a controlled rate near a pilot flame. Concentrated waste containing peroxides: perforation of a container of the waste from a safe distance followed by open burning.
Dipropylene glycol
Dodecylbenzene
Epichlorohydrin: incineration, preferably after mixing with another combustible fuel. Care must be exercised to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.
Ethane
Ethanol
Etahnolamine: controlled incineration; incinerator is equipped with a scrubber of thermal unit to reduce NO_x emissions.
Ethyl acetate
Ethyl acrylate
Ethylamine: controlled incineration; incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions.
Ethylbenzene
Ethyl chloride: incineration, preferably after mixing with another combustible fuel. Care must be exercised to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.
Ethylene
Ethylene cyanohydrin: controlled incineration (oxides of nitrogen are removed from the effluent gas by scrubbers and/or thermal devices).
Ethylenediamine: same as ethylene cyanohydrin.

(continued)

TABLE 2-3 (continued)

Ethylene dibromide: controlled incineration with adequate scrubbing and ash disposal facilities.

Ethylene dichloride: incineration, preferably after mixing with another combustible fuel; care must be exercised to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.

Ethylene glycol

Ethylene glycol monoethyl ether: concentrated waste containing no peroxides; discharge liquid at a controlled rate near a pilot flame. Concentrated waste containing peroxides; perforation of a container of the waste from a safe distance followed by open burning.

Ethyl mercaptan: incineration (2000°F) followed by scrubbing with a caustic solution.

Fatty acids

Formaldehyde

Formic acid

Furfural

Glycerin

n-Heptane

Hexamethylenediamine: incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions.

Hexane

Hydroquinone: incineration (1800°F, 2.0 sec minimum) then scrub to remove harmful combustion products.

Isobutyl acetate

Isopentane

Isophorone

Isoprene

Isopropanol

Isopropyl acetate

Isopropylamine: controlled incineration (incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions).

Isopropyl ether: concentrated waste containing no peroxides; discharge liquid at a controlled rate near a pilot flame. Concentrated waste containing peroxides; perforation of a container of the waste from a safe distance followed by open burning.

Maleic anhydride: controlled incineration; care must be taken that complete oxidation to nontoxic products occurs.

Mercury compounds (organic): incineration followed by recovery/removal of mercury from the gas stream.

Mesityl oxide

Methanol

Methyl acetate

Methyl acrylate

Methylamine: controlled incineration (incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions).

Methyl amyl alcohol

(continued)

TABLE 2-3 (continued)

n-Methylaniline: controlled incineration whereby oxides of nitrogen are removed from the effluent gas by scrubber, catalytic or thermal device.
Methyl bromide: controlled incineration with adequate scrubbing and ash disposal facilities.
Methyl chloride: same as methyl bromide.
Methyl chloroformate: incineration, preferably after mixing with another combustible fuel; care must be exercised to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.
Methyl ethyl ketone
Methyl formate
Methyl isobutyl ketone
Methyl mercaptan: incineration followed by effective scrubbing of the effluent gas.
Methyl methacrylate monomer
Morpholine: controlled incineration (incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions).
Naphtha
Naphthalene
β-Naphthylamine: controlled incineration whereby oxides of nitrogen are removed from the effluent gas by scrubber, catalyst or thermal device.
Nitroaniline: incineration (1800°F, 2.0 sec minimum) with scrubbing for NO_x abatement.
Nitrobenzene: same as nitroaniline
Nitrocellulose: incinerator is equipped with scrubber for NO_x abatement.
Nitrochlorobenzene: incineration (1500°F, 0.5 sec for primary combustion; 2200°F, 1.0 sec for secondary combustion). The formation of elemental chlorine can be prevented through injection of steam or methane into the combustion process. NO_x may be abated through the use of thermal or catalytic devices.
Nitroethane: incineration, large quantities of material may require NO_x removal by catalytic or scrubbing processes.
Nitromethane: same as nitroethane.
Nitrophenol: controlled incineration; care must be taken to maintain complete combustion at all times. Incineration of large quantities may require scrubbers to control the emission of NO_x.
Nitropropane: same as nitroethane.
4-Nitrotoluene: same as nitrophenol.
Nonyl phenol
Octyl alcohol
Oleic acid
Oxalic acid: pretreatment involves chemical reaction with limestone or calcium oxide forming calcium oxalate. This may then be incinerated utilizing particulate collection equipment to collect calcium oxide for recycling.
Paraformaldehyde
Pentachlorophenol: incineration (600° to 900°C) coupled with adequate scrubbing and ash disposal facilities.

(continued)

TABLE 2-3 (continued)

n-Pentane
Perchloroethylene: incineration, preferably after mixing with another combustible fuel; care must be exercised to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.
Phenylhydrazine hydrochloride: controlled incineration whereby oxides of nitrogen are removed from the effluent gas by scrubber, catalytic, or thermal device.
Phthalic anhydride
Polychlorinated biphenyls (PCB's): incineration (3000°F) with scrubbing to remove any chlorine containing products.
Polypropylene glycol methyl ether: concentrated waste containing no peroxides; discharge liquid at a controlled rate near a pilot flame. Concentrated waste containing peroxides; perforation of a container of the waste from a safe distance followed by open burning.
Polyvinyl chloride: incineration, preferably after mixing with another combustible fuel; care must be exercised to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.
Propane
Propionaldehyde
Propionic acid
Propyl acetate
Propyl alcohol
Propylamine: controlled incineration (incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions).
Propylene
Propylene oxide: concentrated waste containing no peroxides; discharge liquid at a controlled rate near a pilot flame. Concentrated waste containing peroxides; perforation of a container of the waste from a safe distance followed by open burning.
Pyridine: controlled incineration whereby oxides of nitrogen are removed from the effluent gas by scrubber, catalytic, or thermal devices.
Quinone: controlled incineration (1800°F, 2.0 sec minimum).
Salicylic acid
Sorbitol
Styrene
Tetrachloroethane: incineration, preferably after mixig with another combustible fuel; care must be exercised to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.
Tetraethyllead: controlled incineration with scrubbing for collection of lead oxides which may be recycled or landfilled.
Tetrahydrofuran: concentrated waste containing peroxides; perforation of a container of the waste from a safe distance followed by open burning.
Tetrapropylene
Toluene

(continued)

TABLE 2-3 (continued)

Toluene diisocyanate: controlled incineration (oxides of nitrogen are removed from the effluent gas by scrubbers and/or thermal devices).
Toluidine: same as toluene diisocyanate.
Trichlorobenzene: incineration, preferably after mixing with another combustible fuel; care must be exercised to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.
Trichloroethane: same as trichlorobenzene.
Trichloroethylene: same as trichlorobenzene.
Trichlorofluoromethane: same as trichlorobenzene.
Triethanolamine: controlled incineration (incinerator is equipped with a scrubber or thermal unit to reduce NO_x emissions).
Triethylamine: same as triethanolamine.
Triethylene glycol
Triethylene tetramine: same as triethanolamine.
Turpentine
Urea: same as triethanolamine.
Vinyl acetate
Vinyl chloride: incineration, preferably after mixing with another combustible fuel; care must be taken to assure complete combustion to prevent the formation of phosgene. An acid scrubber is necessary to remove the halo acids produced.
Xylene

INORGANIC

Inorganic chemicals which may be disposed of (after indicated pretreatment in some cases) by controlled incineration are:

Boron hydrides: with aqueous scrubbing of exhaust gases to remove B_2O_3 particulates.
Fluorine: pretreatment involves reaction with a charcoal bed. The product of the reaction is carbon tetrafluoride which is usually vented. Residual fluorine can be combusted by means of a fluorine-hydrocarbon air burner followed by a caustic scrubber and stack.
Hydrazine: controlled incineration with facilities for effluent scrubbing to abate any ammonia formed in the combustion process.
Hydrazine/hydrazine azide: the blends should be diluted with water and sprayed into an incinerator equipped with a scrubber.
Mercuric chloride: incineration followed by recovery/removal of mercury from the gas stream.
Mercuric nitrate: same as mercuric chloride.
Mercuric sulfate: same as mercuric chloride.
Phosphorus (white or yellow): controlled incineration followed by alkaline scrubbing and particulate removal equipment.

(continued)

TABLE 2-3 (continued)

Sodium azide: Disposal may be accomplished by reaction with sulfuric acid solution and sodium nitrate in a hard rubber vessel. Nitrogen dioxide is generated by this reaction and the gas is run through a scrubber before it is released to the atmosphere. Controlled incineration is also acceptable (after mixing with other combustible wastes) with adequate scrubbing and ash disposal facilities.

Sodium formate: pretreatment involves conversion to formic acid followed by controlled incineration.

Sodium oxalate: pretreatment involves conversion to oxalic acid followed by controlled incineration.

Sodium-potassium alloy: controlled incineration with subsequent effluent scrubbing.

devices, and heat recovery techniques. Foreign technological advances are studied, followed by a listing of manufacturers of incinerator systems and components.

2.2 GENERIC INCINERATION PROCESSES

Incineration of hazardous wastes is an engineered process, with waste destruction being the ultimate goal. As previously stated, a waste's chemical makeup and physical form are important parameters, particularly in selecting the proper incineration process. A system has been devised to classify industrial wastes into five physical forms/combinations as shown in Table 2-4. The system also takes into account the waste's chemical makeup by noting pollutants in the resulting off-gases. This section includes ten processes, corresponding to the numbers in the last column, which are appropriate for thermal destruction of the listed wastes. These wastes are not characteristic of all possible hazardous waste combinations, but the intent of this section is only to present process options. Section 2.3 will look at each process component in more detail and include more complete waste applications [8].

2.2.1 Incineration of Gaseous or Liquid Waste With No Appreciable SO_x or NO_x Production

Figure 2-1 contains four diagrams, one for each of the four configurations of a process to dispose of either a gaseous or liquid waste which produces a flue gas containing acceptable amounts of SO_x and/or NO_x. Configuration 2-1.1 is simply an incinerator which is supplied with waste, fuel, and combustion air. Fuel is required when the waste's combustion energy is insufficient (endothermic) to produce a design operating temperature. An exothermic waste only requires fuel for pilot start-up. A highly exothermic waste requires a cooling medium such as excess air, steam, or water for temperature control.

Configuration 2-1.2 is an incinerator fitted with a heat recovery boiler. The boiler, with economizer, can recover approximately 70% of the heat energy supplied to the incinerator by the waste and fuel.

TABLE 2-4. INDUSTRIAL WASTE AND POLLUTION PROCESS [8]

Classification	Industrial waste	Pollutant	Configuration number
Gas	Asphalt fumes		2-1.1, 2-1.2, 2-1.3, 2-1.4
	Chloroform	Cl_2/HCl	2-2.1, 2-2.2
	Hydrocarbon fume		2-1.1, 2-1.2, 2-1.3, 2-1.4
	HCN H_2	NO_x	2-3.0
	H_2S vents	SO_x	2-2.1, 2-2.2
	Methyl chloride	CL_2/HCl	2-2.1, 2-2.2
	NH_3	NO_x	2-3.0
	NO_x	NO_x	2-3.0
	Phosgene	Cl_2/HCl	2-2.1, 2-2.2
	Tail gas		2-1.1, 2-1.2, 2-1.3, 2-1.4
	VCM[a] vents	Cl_2/HCl	2-2.1, 2-2.2
Gas/solid	Air/maleic anhydride		2-1.1, 2-1.2, 2-1.4
	Air/phthalic anhydride		2-1.1, 2-1.2, 2-1.4
	Air/polyethylene		2-6.1, 2-6.2, 2-6.3
	CO H_2/C		2-6.1, 2-6.2, 2-6.3
	CO H_2/C ash	Particulate	2-7.1, 2-7.2
	Hydrocarbon/C ash	Particulate	2-7.1, 2-7.2
	Propene/Al_2O_3	Particulate	2-5.1, 2-5.2, 2-5.3
Liquid	Acrylonitrile	NO_x	2-3.0
	Carbon tetrachloride	Cl_2/HCl	2-2.1, 2-2.2
	Chloroamine	Cl_2/HCl, NO_x	2-4.0
	Herbicides	Cl_2/HCl	2-2.1, 2-2.2
	Hexachlorobenzene	Cl_2/HCl	2-2.1, 2-2.2
	Hydrazine	NO_x	2-3.0
	H_2O creosote		2-1.1, 2-1.2, 2-1.4
	H_2O isocynates		2-1.1, 2-1.2, 2-1.4
	Nitrosamine	NO_x	2-3.0
	Organic acids		2-1.1, 2-1.2, 2-1.4
	Pesticides	Cl_2/HCl	2-2.1, 2-2.2
	PCB	Cl_2/HCl	2-2.1, 2-2.2
	Pyridine	NO_x	2-3.0
	VCM[a]	Cl_2/HCl	2-2.1, 2-2.2
	High N_2 crude	NO_x	2-10.0
Liquid/solid	APPA[b] solvent/catalyst	Particulate	2-5.1, 2-5.2, 2-5.3
	Biosludge	Particulate	2-5.1, 2-5.2, 2-5.3
	Dye solution	Particulate	2-5.1, 2-5.2, 2-5.3
	Melamine slurry	NO_x	2-8.0
	Phosphorous sludge	H_3PO_4	2-5.1
	Salt solution	Particulate	2-5.1, 2-5.2, 2-5.3
	TPA[c]/catalyst	Particulate	2-5.1, 2-5.2, 2-5.3
	Polypropylene/catalyst	Particulate	2-5.1, 2-5.2, 2-5.3
Solids	APPA[b]/catalyst	Particulate	2-9.0
	Coal fines	Particulate	2-7.1, 2-7.2
	Coke fines	Particulate	2-7.1, 2-7.2
	DNT cellulose	NO_x	2-8.0
	Polyethylene		2-6.1, 2-6.2, 2-6.3
	Sodium organic salts	Particulate	2-7.1, 2-7.2
	Wood chips	Particulate	2-7.1, 2-7.2

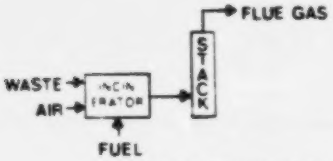
---

[a] Vinyl chloride monomer.

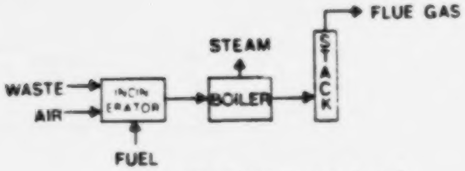
[b] O,O-Dimethyl-phthalimidiomethyl-dithiophosphate.

[c] Phorbol acetate, myristate.

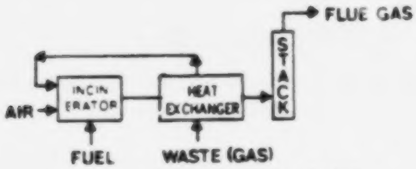
WASTE	EXAMPLE	PRODUCTS OF OXIDATION
GAS	TAIL GAS	FLUE GAS, NO_x, SO_x
LIQUID	ORGANIC ACID	FLUE GAS, NO_x


FLUE GAS
STACK
WASTE
AIR
INCIN ERATOR
FUEL

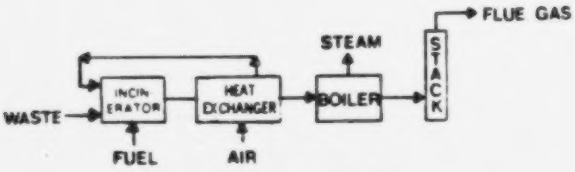
CONFIGURATION 2-1.1


FLUE GAS
STEAM
STACK
WASTE
AIR
INCIN ERATOR
BOILER
FUEL

CONFIGURATION 2-1.2


FLUE GAS
STACK
AIR
INCIN ERATOR
HEAT EXCHANGER
FUEL
WASTE (GAS)

CONFIGURATION 2-1.3


FLUE GAS
STEAM
STACK
WASTE
INCIN ERATOR
HEAT EXCHANGER
BOILER
FUEL
AIR

CONFIGURATION 2-1.4

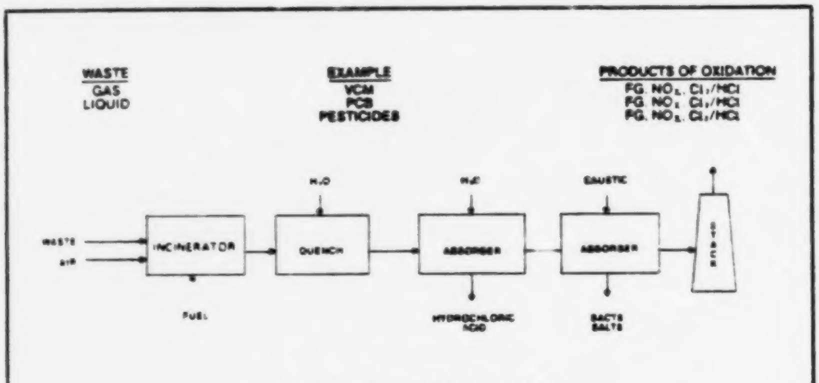
Figure 2-1. Incineration process configurations for disposal of gaseous or liquid waste with no appreciable SO_x or NO_x production.

Configuration 2-1.3 is an incinerator fitted with a gas-to-gas heat exchanger. In the heat exchanger the flue gas is cooled and the waste gas heated.

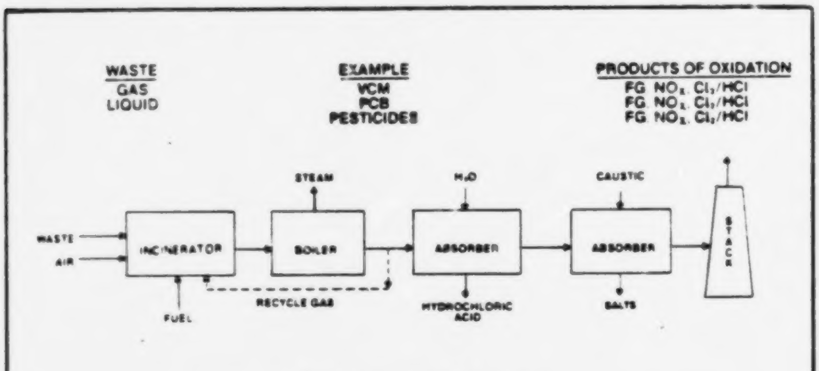
Configuration 2-1.4 is an incinerator fitted with a gas-to-gas heat exchanger and a heat recovery boiler. The preheater heats the incoming combustion air and the boiler extracts the heat available in the flue gas from exchanger outlet temperature. This configuration offers flexibility in the amount of steam produced versus fuel usage.

2.2.2 Incineration of Gaseous Liquid Waste to Control SO_x or Cl_2/HCl

Figure 2-2 contains two block diagrams, one for each of the two configurations of a process to dispose of either a gas or liquid waste which produces flue gas containing excessive amounts of SO_x or Cl_2/HCl.


WASTE
GAS
LIQUID
EXAMPLE
VCM
PCB
PESTICIDES
PRODUCTS OF OXIDATION
FG. NOx. Cl2/HCl
FG. NOx. Cl2/HCl
FG. NOx. Cl2/HCl
H2O
H2O
CAUSTIC
WASTE
AIR
INCINERATOR
QUENCH
ABSORBER
ABSORBER
STACK
FUEL
HYDROCHLORIC ACID
SALTS

CONFIGURATION 2-2.1


WASTE
GAS
LIQUID
EXAMPLE
VCM
PCB
PESTICIDES
PRODUCTS OF OXIDATION
FG. NOx. Cl2/HCl
FG. NOx. Cl2/HCl
FG. NOx. Cl2/HCl
STEAM
H2O
CAUSTIC
WASTE
AIR
INCINERATOR
BOILER
ABSORBER
ABSORBER
STACK
FUEL
RECYCLE GAS
HYDROCHLORIC ACID
SALTS

CONFIGURATION 2-2.2

Figure 2-2. Incineration process configuration for disposal of gaseous or liquid waste with control of excessive SO_x or Cl_2/HCl.

Configuration 2-2.1 consists of an incinerator, a quench section which cools the flue gas to its saturation temperature by directly contacting it with water, two adiabatic absorbers which remove inorganic acids and chlorine and an unlined (no refractory) vent stack.

Water is used in the first absorber to remove a majority of the HCl from the flue gas. The remaining HCl and virtually all the entering Cl_2 leaves the absorber with the flue gas. A second absorber with caustic is used when either the Cl_2 or HCl in this stream exceed allowable levels. This occurs when excessive Cl_2 is formed in the incinerator, or when the first absorber is used to make strong HCl.

Configuration 2-2.1 consists of an incinerator, a heat recovery boiler which produces steam in cooling the flue gas, two adiabatic absorbers, the first being fitted with a lower section of ceramic packing which cools the flue gas to saturation temperature prior to its entry into the acid absorption section. A second absorber for residual HCl and Cl_2 removal and an unlined vent stack follow.

Note that cool flue gas (recycle gas) is recycled to the incinerator for control of operating temperature when the waste is highly exothermic.

2.2.3 Incineration of Gaseous or Liquid Wastes to Control NO_x

Figure 2-3 is a block diagram of a two stage combustion process to dispose of either a gas or liquid that, when oxidized (one stage process), produces a flue gas containing excessive amounts of NO_x. It consists of a reduction furnace in which a high temperature reducing environment (less than stoichiometric air) converts the fuel into H_2, H_2O, CO_2, and CO which converts the NO_x present into N_2, quench section which cools the water gas by directly contacting it with cool recycle gas, an incinerator which converts the H_2 to H_2O and CO to CO_2, heat recovery boiler which produces steam in cooling the flue gas, and an unlined vent stack. Recycle gas cooling in lieu of air, steam, or water is an integral part of this process to minimize NO_x formation and maximize heat recovery.

2.2.4 Incineration of Gaseous or Liquid Waste to Control NO_x and Cl_2/HCl

Figure 2-4 is a block diagram of a process to dispose of either a gas or liquid that produces a flue gas containing Cl_2/HCl and excessive amounts of NO_x. It consists of a reduction furnace in which a high temperature reducing environment converts NO_x into N_2, the Cl_2 into HCl, and fuel into water gas; a quench station which cools the water gas by directly contacting it with recycle gas; an incinerator which converts the H_2 to H_2O, CO to CO_2 and allows the HCl to come to equilibrium producing Cl_2/HCl; a heat recovery boiler which produces steam in cooling the flue gas; an adiabatic absorber, fitted with a lower section of ceramic packing which cools flue gas to saturation temperature prior to its entry into the acid absorption section which removes the inorganic acids; and an unlined vent stack. Recycle gas cooling is an integral part of this process to minimize NO_x formation and maximize heat recovery.

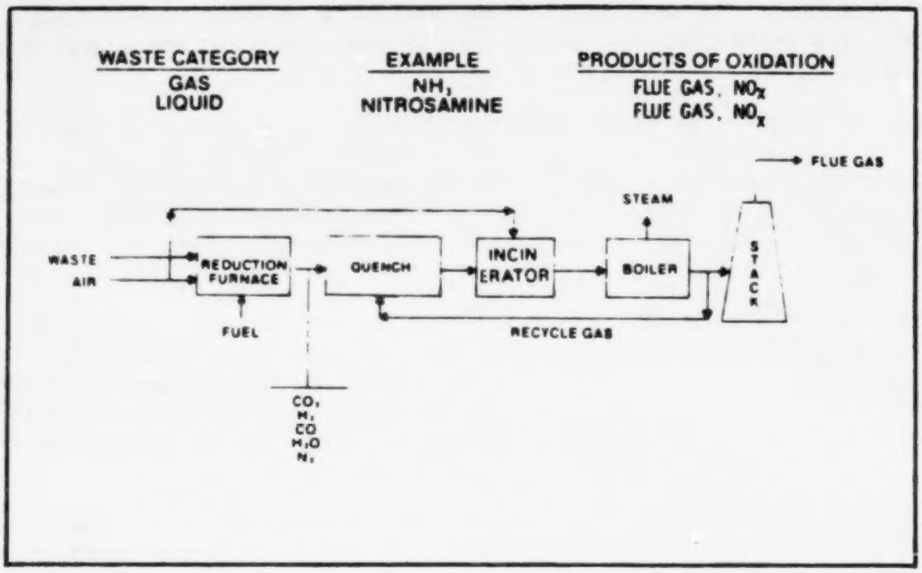

WASTE CATEGORY
GAS
LIQUID
EXAMPLE
NH$_3$
NITROSAMINE
PRODUCTS OF OXIDATION
FLUE GAS, NO$_x$
FLUE GAS, NO$_x$
FLUE GAS
STEAM
WASTE
AIR
REDUCTION FURNACE
QUENCH
INCINERATOR
BOILER
STACK
FUEL
RECYCLE GAS
CO$_2$
H$_2$
CO
H$_2$O
N$_2$

Figure 2-3. Two stage combustion process for disposal of gaseous or liquid waste with control of excessive NO$_x$.

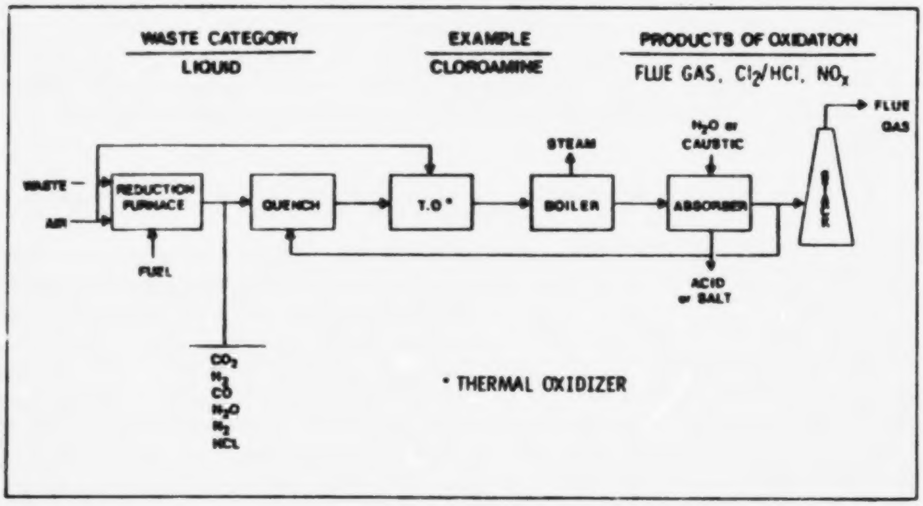

WASTE CATEGORY
LIQUID
EXAMPLE
CLOROAMINE
PRODUCTS OF OXIDATION
FLUE GAS, Cl$_2$/HCl, NO$_x$
FLUE GAS
H$_2$O or CAUSTIC
STEAM
WASTE
AIR
REDUCTION FURNACE
QUENCH
T.O*
BOILER
ABSORBER
STACK
FUEL
ACID or SALT
CO$_2$
H$_2$
CO
H$_2$O
N$_2$
HCL
* THERMAL OXIDIZER

Figure 2-4. Incineration process for disposal of gaseous or liquid waste with control of excessive NO$_x$ and Cl$_2$/HCl.

2.2.5 Incineration of Gaseous or Liquid Waste to Control Particulates

Figure 2-5 is three block diagrams, one for each of three configurations of a process to dispose of either a gaseous or liquid waste which produces flue gas containing excessive amounts of particulate matter.

Configuration 2-5.1 consists of an incinerator, a quench section which cools the flue gas to its saturation temperature by directly contacting it with water, a venturi scrubber which removes the particulate matter, and a vent stack.

Configuration 2-5.2 consists of an incinerator; a conditioning tower which cools the flue gas to either 600°F or 350°F depending upon the dry particulate removal system selected, by directly contacting it with water; either an electrostatic precipitator or bag house for particulate removal; and an unlined vent stack.

Configuration 2-5.3 consists of an incinerator; a conditioning tower, fitted with a Salt Master, which lowers the flue gas to below salt fusion temperature by directly contacting it with recycle gas; a heat recovery boiler which produces steam in cooling the flue gas; either an electrostatic precipitator or bag house for particulate removal; and an unlined vent stack. The Salt Master removes salt from the bottom of the conditioning tower before it can build up to the level sealing the inlet duct to the boiler. This would cause high system pressure drop causing system shutdown. Note, recycle gas may be used for cooling to maximize heat recovery.

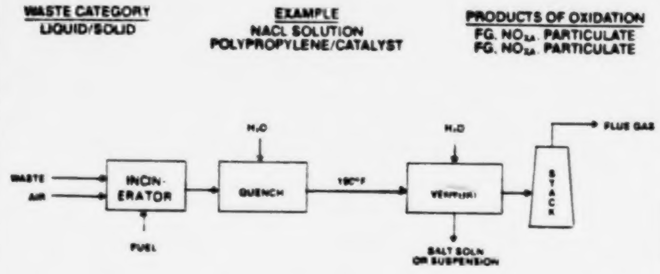
2.2.6 Incineration of Solid Waste with no Appreciable SO_x or NO_x Production

Figure 2-6 is three block diagrams, one for each of three configurations of a process to dispose of a waste containing combustible fine solids (less than 500 μ) which produces flue gas containing acceptable amounts of SO_x and/or NO_x.

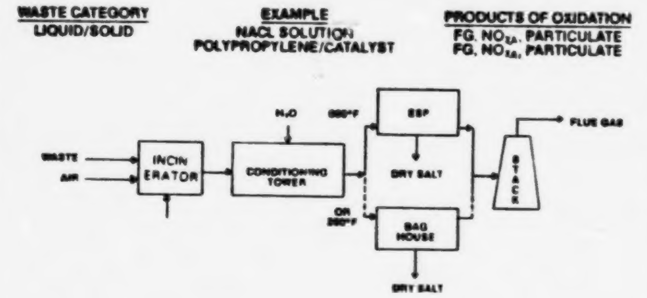
Configuration 2-6.1 consists of a cyclonic incinerator in which a high radial gas velocity causes the denser solid particles to be preferentially "slung" to the wall, thus markedly increasing their retention time, and a refractory lined stack.

Configuration 2-6.2 consists of a cyclonic incinerator fitted with a heat recovery boiler which produces steam in lowering the flue gas temperature, and an unlined vent stack.

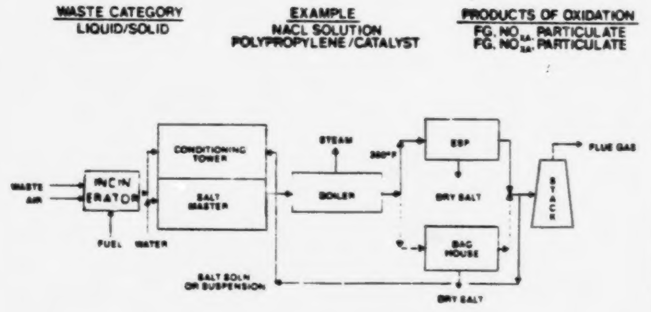
Configuration 2-6.3 consists of a cyclonic incinerator, fitted with a gas-to-gas heat exchanger, which heats the incoming combustion air, and a heat recovery boiler which recovers the heat available in the flue gas, and an unlined vent stack. This configuration offers flexibility in the amount of steam produced versus fuel usage.


WASTE CATEGORY
LIQUID/SOLID
EXAMPLE
NACL SOLUTION
POLYPROPYLENE/CATALYST
PRODUCTS OF OXIDATION
FG, NO_{XA}, PARTICULATE
FG, NO_{XA}, PARTICULATE
WASTE
AIR
INCIN-ERATOR
FUEL
H_2O
QUENCH
H_2O
VENTURI
SALT SOLN OR SUSPENSION
STACK
FLUE GAS

CONFIGURATION 2-5.1

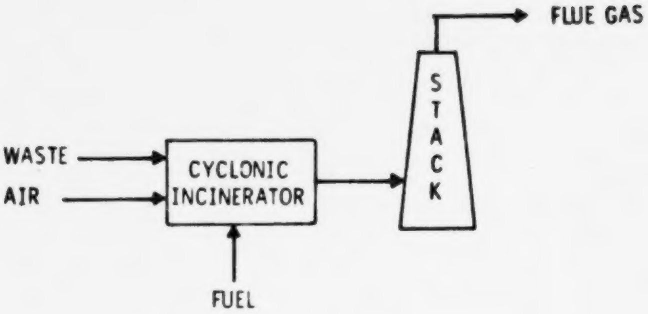

WASTE CATEGORY
LIQUID/SOLID
EXAMPLE
NACL SOLUTION
POLYPROPYLENE/CATALYST
PRODUCTS OF OXIDATION
FG, NO_{XA}, PARTICULATE
FG, NO_{XA}, PARTICULATE
WASTE
AIR
INCIN ERATOR
H_2O
CONDITIONING TOWER
ESP
DRY SALT
OR
BAG HOUSE
DRY SALT
STACK
FLUE GAS

CONFIGURATION 2-5.2

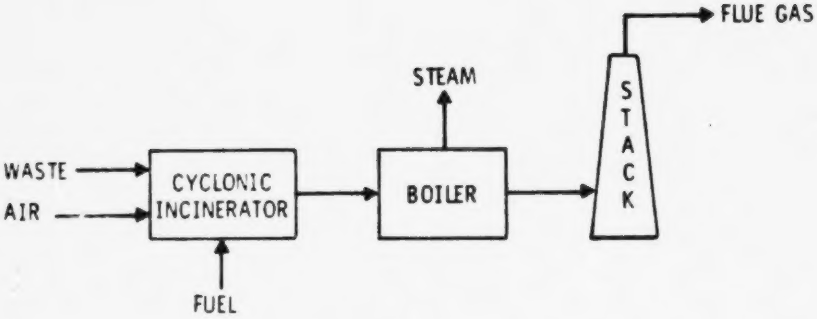

WASTE CATEGORY
LIQUID/SOLID
EXAMPLE
NACL SOLUTION
POLYPROPYLENE/CATALYST
PRODUCTS OF OXIDATION
FG, NO_{XA}, PARTICULATE
FG, NO_{XA}, PARTICULATE
WASTE
AIR
INCIN ERATOR
FUEL
WATER
CONDITIONING TOWER
SALT MASTER
STEAM
BOILER
ESP
DRY SALT
BAG HOUSE
SALT SOLN OR SUSPENSION
DRY SALT
STACK
FLUE GAS

CONFIGURATION 2-5.3

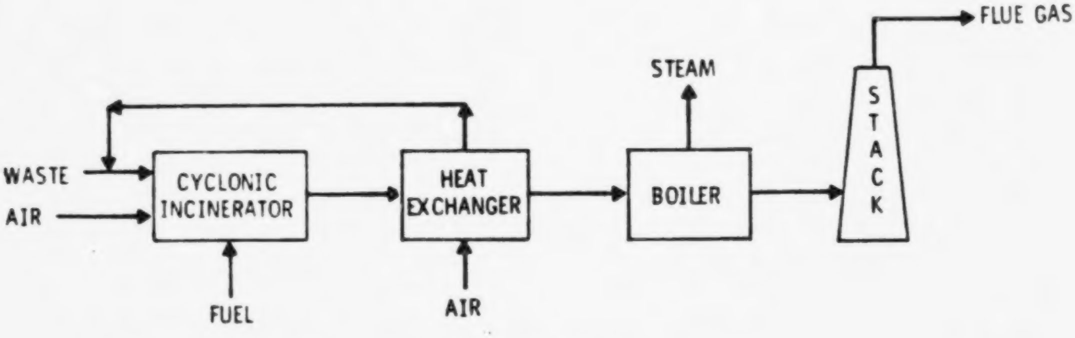
Figure 2-5. Incineration process configurations for disposal of gaseous or liquid waste with control of excessive particulate matter.


FLUE GAS
STACK
WASTE
AIR
CYCLONIC INCINERATOR
FUEL

CONFIGURATION 2-6.1


FLUE GAS
STEAM
STACK
WASTE
AIR
CYCLONIC INCINERATOR
BOILER
FUEL

CONFIGURATION 2-6.2

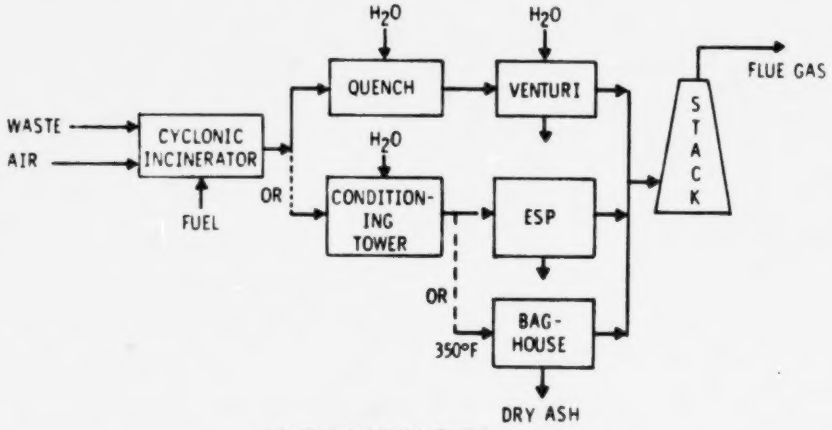

FLUE GAS
STEAM
STACK
WASTE
AIR
CYCLONIC INCINERATOR
HEAT EXCHANGER
BOILER
FUEL
AIR

CONFIGURATION 2-6.3

Figure 2-6. Incineration process configurations for disposal of fine combustible solid waste with no appreciable SO_x or NO_x production.

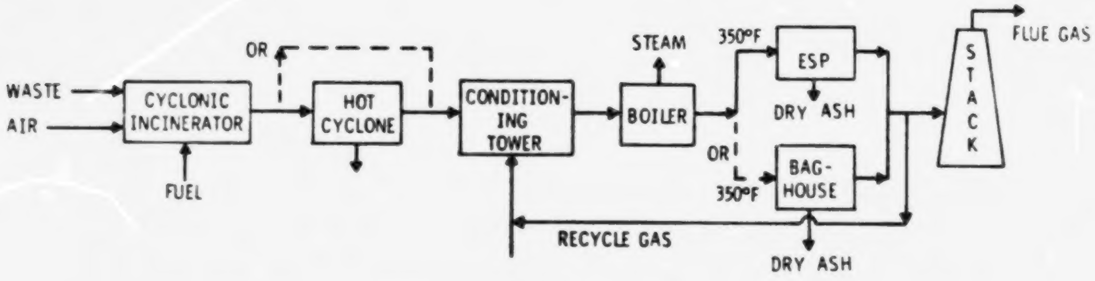
2.2.7 Incineration of Fine Solids in Gaseous Waste to Control Particulates

Figure 2-7 consists of two block diagrams, one for each of two configurations of a process to dispose of a gaseous waste containing a combustible fine solid (less than 500 μ), which produces flue gas containing acceptable amounts of SO_x and/or NO_x and excessive amounts of particulate.



H2O
H2O
FLUE GAS
QUENCH
VENTURI
S T A C K
WASTE
AIR
CYCLONIC INCINERATOR
H2O
OR
CONDITION-ING TOWER
ESP
FUEL
OR
BAG-HOUSE
350°F
DRY ASH

CONFIGURATION 2-7.1



OR
STEAM
350°F
ESP
FLUE GAS
WASTE
AIR
CYCLONIC INCINERATOR
HOT CYCLONE
CONDITION-ING TOWER
BOILER
DRY ASH
S T A C K
FUEL
OR
350°F
BAG-HOUSE
RECYCLE GAS
DRY ASH

CONFIGURATION 2-7.2

Figure 2-7. Incineration process configurations for disposal of gaseous waste containing fine solid particles with control of particulates.

Configuration 2-7.1 consists of a cyclonic incinerator and either a quench column, which by directly contacting the flue gas with water, cools it to its saturation temperature, and a venturi scrubber which removes the particulate matter, or a conditioning tower which by directly contacting the flue gas with recycle gas cools it, depending on the dry particulate removal system selected, and either an electrostatic precipitator or bag house for particulate removal, and an unlined vent stack.

Configuration 2-7.2 consists of a cyclonic incinerator, a hot cyclone for large particulate removal and/or conditioning tower which by directly contacting the flue gas with recycle gas cools it to below ash fusion temperature, a heat recovery boiler which produces steam in cooling the flue gas, either an electrostatic precipitator or bag house for particulate removal, and an unlined vent stack. Recycle gas may be used for cooling to maximize heat recovery.

2.2.8 Incineration of Fine Solid Waste to Control NO_x

Figure 2-8 is a block diagram of a process to dispose of a waste that contains combustible solids in the size range of 10 to 500 μ that produces a flue gas containing excessive amount of NO_x. It consists of a cyclonic reduction furnace in which a high radial velocity, high temperature reducing environment (less than stoichiometric air) converts the bound nitrogen into N_2 and the fuel into water gas, a quench section which cools the water gas, and an incinerator which coverts the H_2 to H_2O and CO to CO_2, a heat recovery boiler which produces steam in cooling the flue gas and an unlined vent stack. Recycle gas cooling, (not air, steam, or water) is an integral part of the process to minimize NO_x formation and maximize heat recovery.

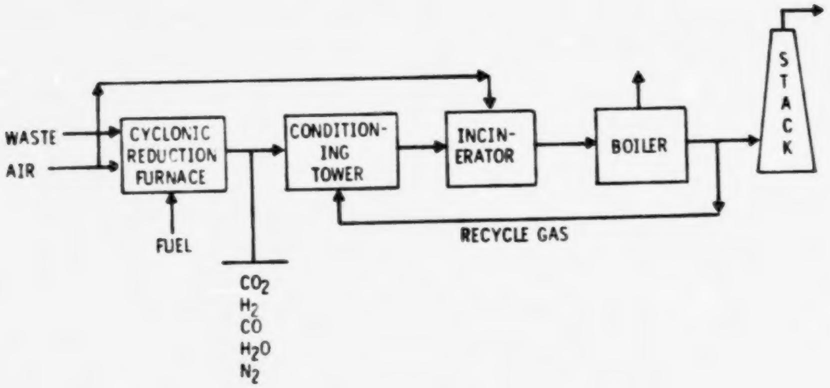


Figure 2-8. Incineration process for disposal of fine solid waste without control of NO_x.

2.2.9 Incineration of Solid Waste to Control Particulates

Figure 2-9 is a block diagram of a process to dispose of plastic chunks containing catalyst which produces flue gas containing excessive amounts of particulate. It consists of a reduction furnace which burns the waste in a pool on the furnace floor in a reducing environment producing a moderate Btu gas; an incinerator; a conditioning tower which, by directly contacting the flue gas with recycle gas, cools it to below salt fusion temperature; a heat recovery boiler which produces steam in cooling the flue gas; either an electrostatic precipitator or bag house for particulate removal; and an unlined vent stack. Recycle gas may be used for cooling to maximize heat recovery.

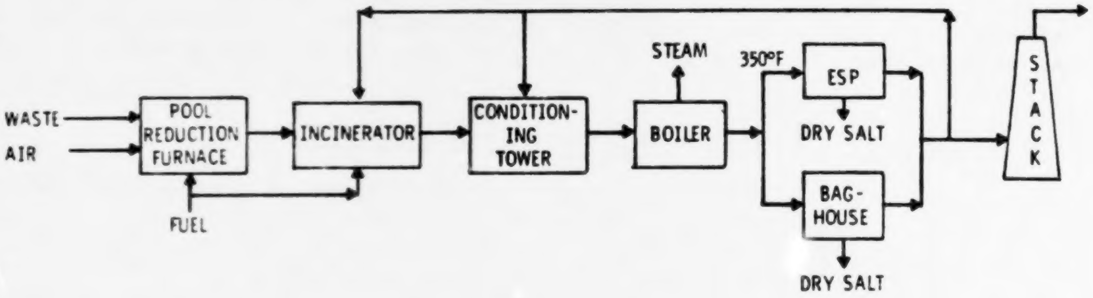

WASTE
AIR
POOL REDUCTION FURNACE
FUEL
INCINERATOR
CONDITIONING TOWER
STEAM
BOILER
350°F
ESP
DRY SALT
BAG-HOUSE
DRY SALT
STACK

Figure 2-9. Incineration process for disposal of solid plastic waste containing catalyst with control of particulates.

2.2.10 Incineration of High Nitrogen Crude to Control NO_x

Figure 2-10 is a block diagram of a two stage combustion process to burn a high nitrogen crude that, when oxidized (one stage), produces a flue gas containing excessive amounts of NO_x.

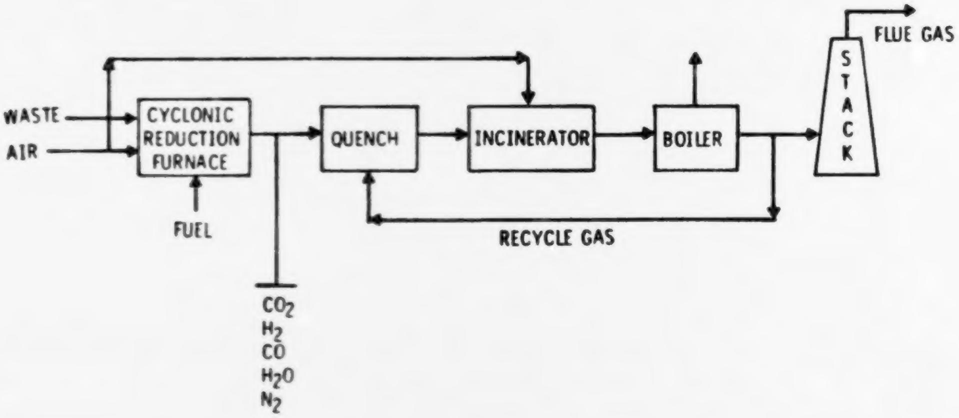

FLUE GAS
WASTE
AIR
CYCLONIC REDUCTION FURNACE
FUEL
QUENCH
INCINERATOR
BOILER
STACK
RECYCLE GAS
CO_2
H_2
CO
H_2O
N_2

Figure 2-10. Two-stage combustion process for disposal of high nitrogen crude with control of NO_x.

This process is similar in concept to process three. It consists of a reduction boiler, substituting for process three's reduction furnace, in which a high temperature reducing (less than stoichiometric air) converts the high nitrogen crude into H_2, H_2O, CO_2, and CO which limits the formation of NO_x and reduces any formed NO_x into N_2, a smaller quench section than process three which cools the water gas by directly contacting it with cool recycle gas, an incinerator which converts the H_2 to H_2O and CO to CO_2, convection boiler which produces steam in cooling the flue gas, and an unlined vent stack. Recycle gas cooling (in lieu of air, steam, or water) is an integral part of this process to minimize NO_x formation and maximize heat recovery.

2.3 INCINERATOR SYSTEM COMPONENTS

This section deals with the individual components introduced in the previous sections. Commercially available and emerging incineration technologies are examined, as well as pertinent air pollution control devices and heat recovery techniques. An accompanying matrix (Table 2-5) integrating particular waste types with these various components is presented at the end of Section 2.3.

2.3.1 Commercially Available Incineration Technologies

Five technologies will be studied in this subsection, with emphasis given to two major hazardous waste destruction techniques, rotary kiln and liquid injection incineration. The less frequently used techniques are fluidized bed and multiple hearth incinerators, along with the fifth technique, coincineration, usually involving a variation of rotary kiln or multiple hearth applications. Each technology is described, illustrated, and discussed as to its advantages, disadvantages, and applications.

2.3.1.1 Rotary Kiln [6, 7, 9-14]--

Operation -

Rotary kiln incinerators are generally refractory-lined cylindrical shells mounted at a slight incline from the horizontal plane. The speed of rotation may be used to control the residence time and mixing with combustion air. They are generally used by industry, the military, and municipalities to degrade solid and liquid combustible wastes, but combustible gases may also be oxidized. Recently, rotary kiln incinerators have been used to successfully dispose of obsolete chemical warfare agents and munitions. Figure 2-11 is a schematic of what a general rotary kiln system involves [7, 9]. This schematic is typical of most rotary kilns, including small portable units currently being used in hazardous waste disposal site restoration and demilitarization projects.

Two types of rotary kilns are currently being manufactured in the U.S. today, cocurrent (burner at the front end with waste feed) and countercurrent (burner at the back end). For a waste which easily sustains combustion, the positioning of the burner is arbitrary from an incineration standpoint; both types will destroy a waste. However, for a waste having low combustibility (such as

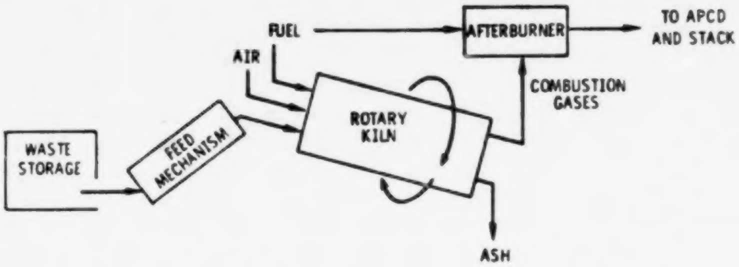


Figure 2-11. Rotary kiln incinerator schematic.

a high water volume sludge), the countercurrent design offers the advantage of controlling temperature at both ends, which all but eliminates problems such as overheating the refractory lining. The countercurrent flow technique has been reputed to carry excessive ash over into the air pollution control system due to the associated higher velocities involved, however, this condition also increases the turbulence during combustion which is generally a desirable factor*.

Optimal length to diameter (L/D) ratios have ranged from 2 to 10, and rotational speeds of 1 to 5 FPM at the kiln periphery are common, depending on the nature of the waste. Residence times vary from a few seconds for a highly combustible gas, to a few hours for a low combustible solid waste. A typical feed capacity range is 600 kg/hr to 2,000 kg/hr for solids, and 630 L/hr to 2250 L/hr for liquids at temperatures ranging from 800°C to 1600°C. Since rotary kilns are normally totally refractory-lined and have no exposed metallic parts, they may operate at high incineration temperatures while experiencing minimal corrosion effects. Solid wastes, sometimes packed in fiber drums, are generally fed to the kiln by conveyor. Liquids and sludges are pumped in, with liquids usually being strained, then atomized with steam or air. The kiln and liquid burner are equipped with natural gas ignitors and gas burners for initial refractory heating, flame stability, and supplemental heat if necessary [7, 9].

Afterburners are commonly used to ensure complete combustion of flue gases prior to treatment for air pollutants. Resource recovery (depending on the waste) and heat recovery are also common practices as initial steps to treatment of flue gases.

Types of Wastes -

Numerous hazardous wastes which previously were disposed of in potentially harmful manners (ocean dumping, landfilling and deep-well injection) are currently being safely and economically destroyed using rotary kiln incinerators combined with proper flue gas handling. Included in this list of primarily toxic wastes are polyvinyl chloride wastes, PCB wastes from capacitors, obsolete munitions, and obsolete chemical warfare agents such as GB, VX, and mustard. Beyond these specific wastes, the rotary kiln incinerator is generally applicable to the destruction and ultimate disposal of any form of hazardous waste material which is combustible at all. Table 2-5, at the end of this section, helps illustrate this fact. Unlikely candidates are noncombustibles such as heavy metals, high moisture content wastes, inert materials, inorganic salts, and the general group of materials having a high inorganic content.

---

*Per phone call to Will Kepner of Bartlett-Snow, Chicago, Illinois.

Advantages -

(1) Will incinerate a wide variety of liquid and solid hazardous wastes.
(2) Will incinerate materials passing through a melt phase.
(3) Capable of receiving liquids and solids independently or in combination.
(4) Feed capability for drums and bulk containers.
(5) Adaptable to wide variety of feed mechanism designs.
(6) Characterized by high turbulence and air exposure of solid wastes.
(7) Continuous ash removal which does not interfere with the waste oxidation.
(8) No moving parts inside the kiln (except when chains are added).
(9) Adaptable for use with a wet gas scrubbing system.
(10) The retention or residence time of the nonvolatile component can be controlled by adjusting the rotational speed.
(11) The waste can be fed directly into the kiln without any preparation such as preheating, mixing, etc.
(12) Rotary kilns can be operated at temperatures in excess of 2,500°F (1,400°C), making them well suited for the destruction of toxic compounds that are difficult to thermally degrade.
(13) The rotational speed control of the kiln also allows a turndown ratio (maximum to minimum operating range) of about 50%.

Disadvantages -

(1) High capital cost for installation.
(2) Operating care necessary to prevent refractory damage; thermal shock is a particularly damaging event.
(3) Airborne particles may be carried out of kiln before complete combustion.
(4) Spherical or cylindrical items may roll through kiln before complete combustion.
(5) The rotary kiln frequently requires additional makeup air due to air leakage via the kiln end seals.
(6) Drying or ignition grates, if used prior to the rotary kiln, can cause problems with melt plugging of grates and grate mechanisms.
(7) High particulate loadings.
(8) Relatively low thermal efficiency.
(9) Problems in maintaining seals at either end of the kiln are a significant operating difficulty.
(10) Drying of aqueous sludge wastes or melting of some solid wastes can result in clinker or ring formation on refractory walls.

2.3.1.2 Liquid Injection [3, 5, 6, 10, 11, 13-15]--

Operation -

Liquid injection incinerators are currently the most commonly used incinerator for hazardous waste disposal. A wide variety of units is marketed today, with the 2 major types being horizontally- and vertically-fired units. A less common unit is the tangentially-fired vortex combustor; all three of these units are schematically represented in Figures 2-12 through 2-14. As the name implies, the liquid injection incinerator is confined to hazardous liquids, slurries and sludges with a viscosity value of 10,000 SSU* or less [7]. The reason for this limitation being that a liquid waste must be converted to a gas prior to combustion. This change is brought about in the combustion chamber, and is generally expedited by increasing the waste surface area through atomization. An ideal size droplet is about 40 μ or less, and is attainable mechanically using rotary cup or pressure atomization, or via gas-fluid nozzles and high pressure air or steam.

The key to efficient destruction of liquid hazardous wastes lies in minimizing unevaporated droplets and unreacted vapors. Just as for the rotary kiln, temperature, residence time, and turbulence may be optimized to increase destruction efficiencies. Typical combustion chamber residence time and temperature ranges are 0.5 to 2 seconds and 700°C to 1650°C, respectively. Liquid injection incinerators are variable dimensionally, and have feed rates up to 5,600 L/hr.

The combustion chamber is a refractory-lined cylinder. Burners are normally located in the chamber in such a manner that the flames do not impinge on the refractory walls. The combustion chamber wall can be actively cooled by process air prior to its entry into the combustion zone, thus preheating the air to between 150°C and 370°C .

Liquid waste fuel is transferred from drums into a feed tank. The tank is pressurized with nitrogen, and waste is fed to the incinerator using a remote control valve and a compatible flowmeter. The fuel line is purged with N_2 after use. A recirculation system is used to mix the tank contents [17]. Normally a gas (for example, propane) preheats the incinerator system to an equilibrium temperature of approximately 815°C before introduction of the waste liquid.

Of the three types of units discussed earlier, the horizontal and vertical are basically similar in operating conditions. The tangentially-fired unit is known to have a much higher heat release and generally superior mixing than the previous two units, making it more attractive for disposal of high water content wastes and less combustible materials. However, these conditions lend to increased deterioration of the refractory lining from thermal effects and erosion [7].

---

*To obtain the Saybolt universal viscosity equivalent to a kinematic viscosity determined at t°F, multiply the equivalent Saybolt universal viscosity at 100°F by 1 + (t - 100) 0.000064; e.g., 10 centistokes at 210°F are equivalent to 58.8 x 1.0070, or 59.2 SSU at 210°F. (Handbook of Chemistry and Physics, 45th edition).

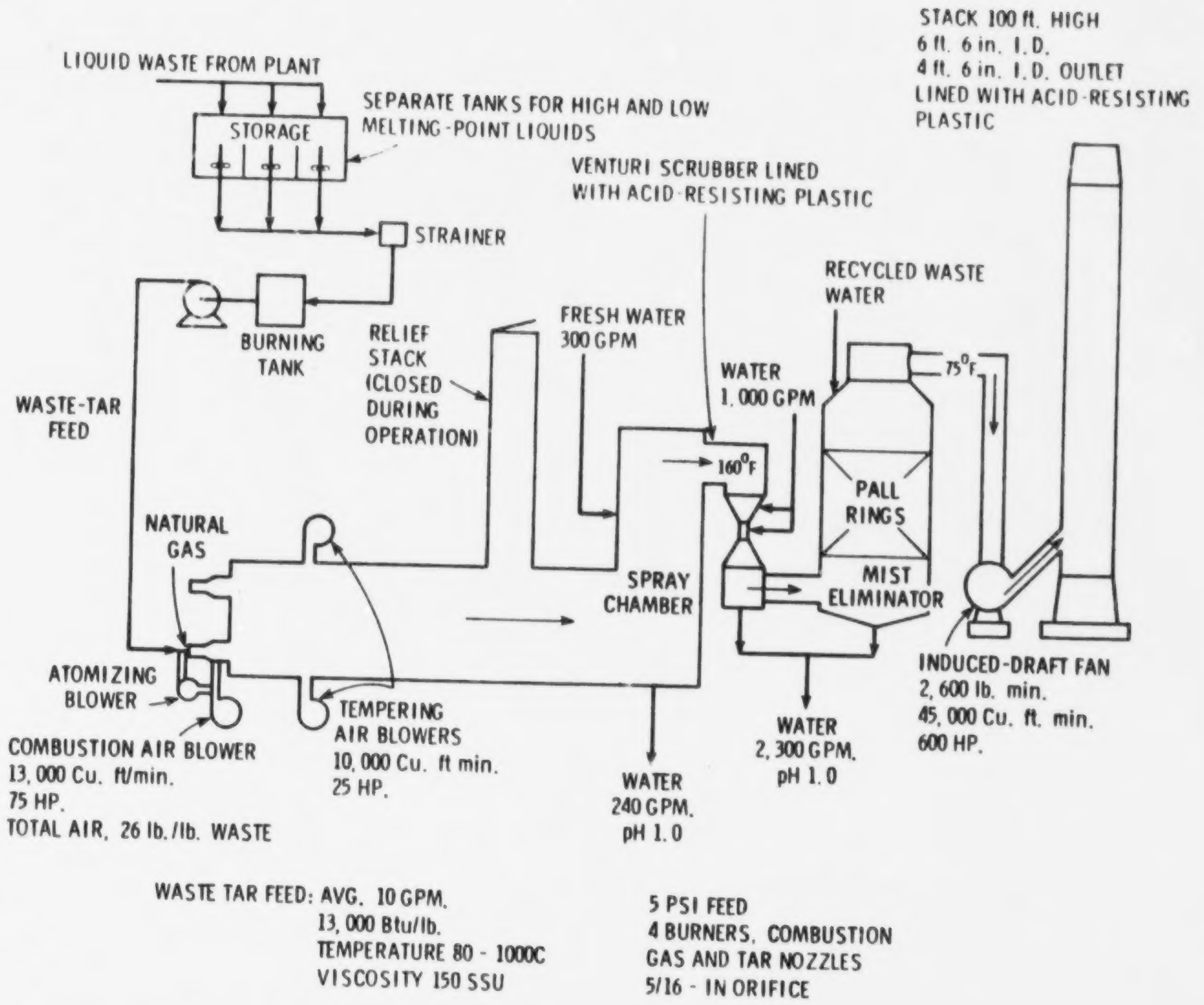

LIQUID WASTE FROM PLANT
STORAGE
SEPARATE TANKS FOR HIGH AND LOW MELTING-POINT LIQUIDS
STRAINER
BURNING TANK
WASTE-TAR FEED
RELIEF STACK (CLOSED DURING OPERATION)
FRESH WATER 300 GPM
VENTURI SCRUBBER LINED WITH ACID-RESISTING PLASTIC
WATER 1,000 GPM
160°F
RECYCLED WASTE WATER
75°F
PALL RINGS
MIST ELIMINATOR
STACK 100 ft. HIGH
6 ft. 6 in. I.D.
4 ft. 6 in. I.D. OUTLET
LINED WITH ACID-RESISTING PLASTIC
NATURAL GAS
SPRAY CHAMBER
ATOMIZING BLOWER
COMBUSTION AIR BLOWER
13,000 Cu. ft/min.
75 HP.
TOTAL AIR, 26 lb./lb. WASTE
TEMPERING AIR BLOWERS
10,000 Cu. ft min.
25 HP.
WATER 240 GPM. pH 1.0
WATER 2,300 GPM. pH 1.0
INDUCED-DRAFT FAN
2,600 lb. min.
45,000 Cu. ft. min.
600 HP.
WASTE TAR FEED: AVG. 10 GPM.
13,000 Btu/lb.
TEMPERATURE 80 - 1000C
VISCOSITY 150 SSU
5 PSI FEED
4 BURNERS, COMBUSTION GAS AND TAR NOZZLES
5/16 - IN ORIFICE

Figure 2-12. Horizontally-fired liquid injection incinerator schematic [7].

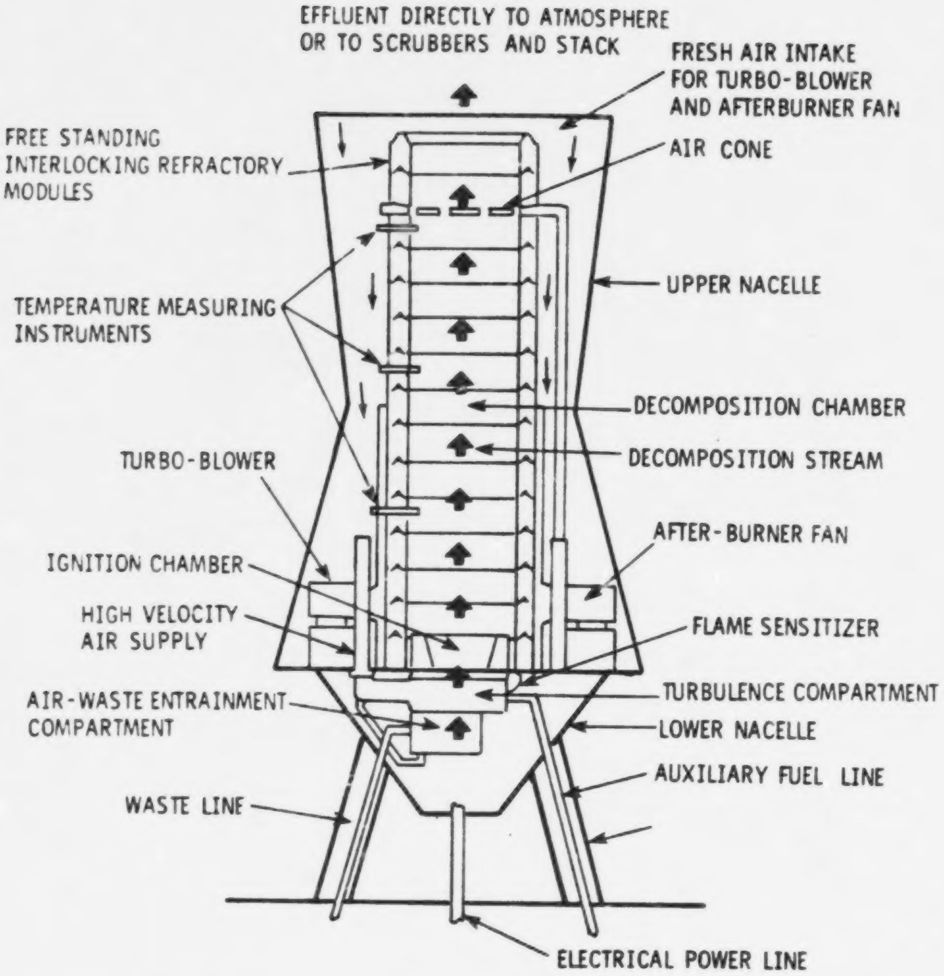

EFFLUENT DIRECTLY TO ATMOSPHERE OR TO SCRUBBERS AND STACK
FRESH AIR INTAKE FOR TURBO-BLOWER AND AFTERBURNER FAN
FREE STANDING INTERLOCKING REFRACTORY MODULES
AIR CONE
UPPER NACELLE
TEMPERATURE MEASURING INSTRUMENTS
DECOMPOSITION CHAMBER
DECOMPOSITION STREAM
TURBO-BLOWER
AFTER-BURNER FAN
IGNITION CHAMBER
HIGH VELOCITY AIR SUPPLY
FLAME SENSITIZER
AIR-WASTE ENTRAINMENT COMPARTMENT
TURBULENCE COMPARTMENT
LOWER NACELLE
AUXILIARY FUEL LINE
WASTE LINE
ELECTRICAL POWER LINE

Figure 2-13. Vertically-fired liquid injection incinerator schematic [7].

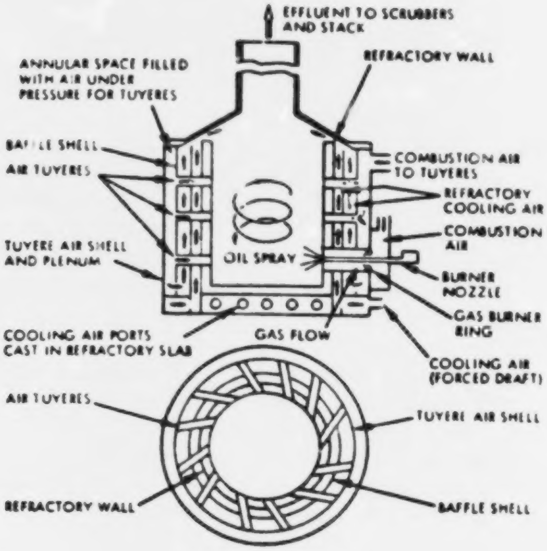

EFFLUENT TO SCRUBBERS AND STACK
ANNULAR SPACE FILLED WITH AIR UNDER PRESSURE FOR TUYERES
REFRACTORY WALL
BAFFLE SHELL
AIR TUYERES
COMBUSTION AIR TO TUYERES
REFRACTORY COOLING AIR
COMBUSTION AIR
TUYERE AIR SHELL AND PLENUM
OIL SPRAY
BURNER NOZZLE
GAS BURNER RING
COOLING AIR PORTS CAST IN REFRACTORY SLAB
GAS FLOW
COOLING AIR (FORCED DRAFT)
AIR TUYERES
TUYERE AIR SHELL
REFRACTORY WALL
BAFFLE SHELL

Figure 2-14. Tangentially-fired vortex combustor liquid injection incinerator schematic [7].

Types of Wastes -

Liquid injection incinerators are capable of handling any combustible liquid hazardous waste with the viscosity constraints previously mentioned. They have been widely used in industry for a broad range of liquid wastes, as shown in Table 2-5 (at the end of Section 2.3). In the case of the rotary kiln incinerator, wastes which are unlikely candidates for destruction are noncombustibles such as heavy metals, high moisture content wastes, inert materials, inorganic salts, and the general group of materials having high inorganic content.

Advantages -

(1) Capable of incinerating a wide range of liquid hazardous wastes.
(2) No continuous ash removal system is required other than for air pollution control.
(3) Capable of a fairly high turndown ratio.
(4) Fast temperature response to changes in the waste fuel flowrate.
(5) Virtually no moving parts.
(6) Low maintenance costs.

Disadvantages -

(1) Only wastes which can be atomized through a burner nozzle can be incinerated.
(2) Heat content of waste burned must maintain adequate ignition and incineration temperatures or a supplemental fuel must be provided.
(3) Burners susceptible to pluggage (burners are designed to accept a certain particle size; therefore, particle size is a critical parameter for successful operation).
(4) Burner may or may not be able to accept a material which dries and cakes as it passes through the nozzles.

2.3.1.3 Fluidized Bed [6, 10, 11, 13-15, 17, 18]--

Operation -

Fluidized bed incinerators are vessels containing a bed of inert granular material, usually sand, which is kept at temperatures in a range from 450 to 850°C. Fluidizing air is passed through a distributor plate below the bed and agitates the heated granular material. Hazardous waste material and auxiliary fuel are injected radially in proportionately small amounts and mixed with the bed material which transfers heat to the waste. The waste in turn combusts and returns energy to the bed [7].

This process is pictured in Figure 2-15, which represents a typical fluidized bed incinerator. The reactor vessel is commonly about 7-8 meters in diameter and 10 meters high. Bed depths are typically 1 meter while at rest, and 2 meters during operation. Variations in the depth affect both residence time and pressure drop, resulting in a compromised depth which optimizes residence time and excess air to ensure complete combustion [18].

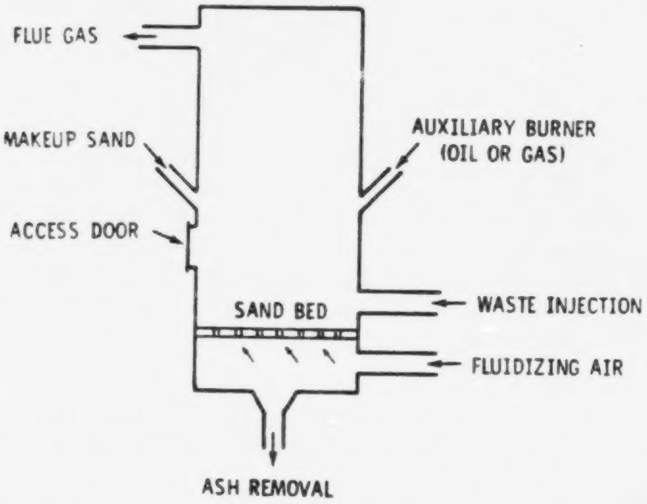


Figure 2-15. Typical fluidized bed incinerator schematic.

Bed temperatures are restricted by the softening point of the bed medium, which is about 900°C for sand. These high temperatures allow for reaction of gaseous wastes and combustion gases above the bed as well. Gas velocities in the bed are generally maintained near 2 meters per second. The gas velocity is constrained by the terminal velocity, and thus particle size. Too high a velocity results in bed attrition and heavy particulate loading of the flue gas, while a lower velocity reduces pressure drop and results in lower power requirements. The residence time is generally around 12 to 14 seconds for a liquid hazardous waste [7, 18].

Types of Wastes -

Most fluidized bed applications to hazardous waste in the literature involve incineration of sludges and slurries. The type and composition of the waste are key design parameters determining feed mechanisms, processing, and bed specifics. A homogeneous combustible liquid may be immediately injected, but a nonhomogeneous sludge having moderate combustion potential and interspersed with large solid matter will require sorting, drying, shredding, and special feed considerations prior to entering the reactor. Despite the need for pretreatment, the fluidized bed is capable of handling most any waste that the rotary kiln can, depending on the heat limitations of the bed material.

Advantages -

(1) General applicability for the disposal of combustible hazardous solids, liquids, and gaseous wastes.
(2) Simple design concept, requiring no moving parts in the combustion zone.
(3) Compact design due to high heating rate per unit volume (100,000 to 200,000 Btu/hr-ft^3 (900,000 to 1,800,000 kg-cal/hr-m^3) which results in relatively low capital costs.
(4) Relatively low gas temperatures and excess air requirements which tend to minimize nitrogen oxide formation and contribute to smaller, lower cost emission control systems.
(5) Long incinerator life and low maintenance costs.
(6) Large active surface area resulting from fluidizing action enhances the combustion efficiency.
(7) Fluctuation in the feed rate and composition are easily tolerated due to the large quantities of heat stored in the bed.
(8) Provides for rapid drying of high-moisture-content material, and combustion can take place in the bed.
(9) Proper bed material selection suppresses acid gas formation; hence, reduced emission control requirements.
(10) Provides considerable flexibility for shockload of waste; i.e., large quantities of waste being dumped in the bed at a single time.

Disadvantages -

(1) Difficult to remove residual materials from the bed.
(2) Requires fluid bed preparation and maintenance.
(3) Feed selection must avoid bed degradation caused by corrosion or reactions.
(4) May require special operating procedures to avoid bed damage.
(5) Operating costs are relatively high, particularly power costs.
(6) Possible operating difficulties with materials high in moisture content.
(7) Formation of eutectics is a serious problem.
(8) Hazardous waste incineration practices have not been fully developed.
(9) Not well suited for irregular, bulky wastes, tarry solids, or wastes with a fusible ash content.

2.3.1.4 Multiple Hearth [1, 3, 5, 6, 10, 13 - 15]--

Operation -

A typical multiple hearth furnace includes a refractory-lined steel shell, a central shaft that rotates, a series of solid flat hearths, a series of rabble arms with teeth for each hearth, an air blower, fuel burners mounted on the walls, an ash removal system, and a waste feeding system. Side ports for tar injection, liquid waste burners, and an afterburner may also be included. Figure 2-16 illustrates the incinerator and its typical flow scheme.

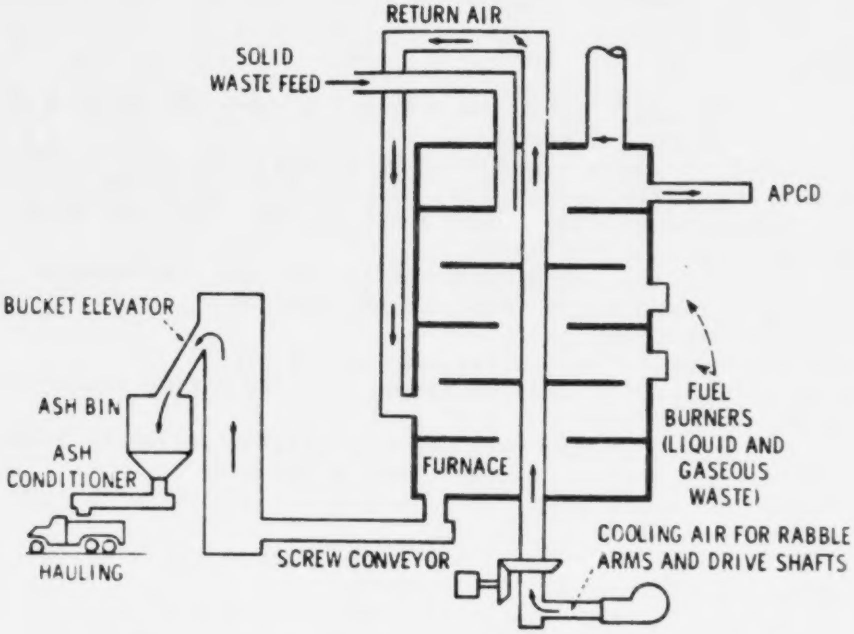

RETURN AIR
SOLID WASTE FEED
APCD
BUCKET ELEVATOR
ASH BIN
ASH CONDITIONER
HAULING
SCREW CONVEYOR
FURNACE
FUEL BURNERS (LIQUID AND GASEOUS WASTE)
COOLING AIR FOR RABBLE ARMS AND DRIVE SHAFTS

Figure 2-16. Typical multiple hearth incinerator schematic.

Sludge and/or granulated solid combustible waste is fed through the furnace roof by a screw feeder or belt and flapgate. The rotating air-cooled central shaft with air-cooled rabble arms and teeth distributes the waste material across the top hearth to drop holes. The waste falls to the next hearth and then the next until discharged as ash at the bottom. The waste is agitated as it moves across the hearths to make sure fresh surface is exposed to hot gases.

Units range from 1.8 m to 7.6 m in diameter and from 3.6 m to 23 m in height. The diameter and number of hearths are dependent on the waste feed, the required processing time, and the type of thermal processing employed. Generally, the uppermost hearth is used as an afterburner. Normal incineration usually requires a minimum of six hearths, while pyrolysis applications require a greater number [6].

The rabble arms and teeth located on the central shaft all rotate in the same direction; additional agitation of the waste (back rabbling) is accomplished by reversing the angles of the rabble teeth. Waste retention time is controlled by the design of the rabble tooth pattern and the rotational speed of the central shaft [3].

Liquid and/or gaseous combustible wastes may be injected into the unit through auxiliary burner nozzles. This utilization of liquid and gaseous waste represents an economic advantage because it reduces secondary fuel requirements, thus lowering operating costs [3].

A multiple hearth unit generally has three operating zones, the uppermost hearths where feed is dried (350° to 550°C), the incineration zone (800° to 1000°C), and the cooling zone (200° to 350°C). Exit gases have good potential for heat recovery, being around 300° to 600°C. Temperatures on each hearth can be maintained using supplemental fuel [7].

Types of Waste -

Multiple hearth units are best suited for hazardous sludge disposal. As in the case of fluidized bed incinerators, solid wastes generally have to be pretreated prior to successful incineration. Allowing for this, multiple hearths are capable of handling the same hazardous wastes as rotary kilns. Unlikely candidates are heavy metals, inert materials, inorganic salts, and the general group of materials having high inorganic content.

Advantages -

(1) The retention or residence time in multiple hearth incinerators is usually higher for hazardous materials having low volatility than in other incinerator configurations.
(2) Large quantities of water can be evaporated.
(3) A wide variety of wastes with different chemical and physical properties can be handled.
(4) Multiple hearth incinerators are able to utilize many fuels including natural gas, reformer gas, propane, butane, oil, coal dust, waste oils, and solvents.
(5) Because of its multizone configuration, fuel efficiency is high and typically improves with the number of hearths used.
(6) Fuel burners can be added to any of the hearths to maintain a desired temperature profile.
(7) Multiple hearth incinerators are capable of a turndown ratio of 35%.
(8) High fuel efficiency is allowed by the multizone configuration.

Disadvantages -

(1) Due to the longer residence times of the waste materials, temperature response throughout the incinerator when the burners are adjusted is usually very slow.
(2) It is difficult to control the firing of supplementary fuels as a result of this slow response.

(3) Maintenance costs are high because of the moving parts (rabble arms, main shaft, etc.) subjected to combustion conditions.
(4) Multiple hearth incinerators are susceptible to thermal shock resulting from frequent feed interruptions and excessive amounts of water in the feed. These conditions can lead to early refractory and hearth failures.
(5) If used to dispose of hazardous wastes, a secondary combustion chamber probably will be necessary and different operating temperatures might be necessary.
(6) Not well suited for wastes containing fusible ash, wastes which require extremely high temperature for destruction, or irregular bulky solids.

2.3.1.5 Coincineration--

Operation -

Hazardous waste coincineration has been performed in a rotary kiln pyrolyzer and a multiple hearth incinerator on a test basis. This technique is used to supply needed Btu's when the principal waste to be burned possesses insufficient heat content to be autogenic. Coincineration generally refers to the joint incineration of hazardous waste, in any form, with refuse and/or sludge. This is not a unique technology; any existing incineration process can be used for this special case of mixing waste streams to obtain better destruction of a particularly intractable waste material.

The rotary kiln pyrolyzer test unit used for Kepone incineration contained the following components [21]:

- Waste feed system
- Rotary kiln pyrolyzer
- Afterburner
- Air pollution control device system

Kepone-contaminated sludge was simulated by the mechanical mixing of appropriate amounts of Kepone solution in acetic acid into sludge in the feed tank. The latter was a cylindrical vessel, 86 cm in diameter and 60 cm high fitted with a pneumatic stirrer. The 10 cm outlet port in the conical bottom of the feed tank was fitted with a screen and connected to a two-stage, variable speed pump. The discharge line was fitted with a pressure relief valve and with provisions to inject sludge from the feed tank or water from the mains. The feed line, which entered the kiln within the kiln discharge line, was water-jacketed to prevent caking within the feed line. At the end of a run, the feed line was flushed with water [20].

The rotary kiln pyrolyzer 1.5 m in diameter and 3.0 m in length, was fitted with rotary seal charge and discharge connections so as to minimize the leakage of gases into or out of the kiln. It was heated directly by the hot gases from a 0.923-J/s burner to maintain a nominal temperature of 500°C. Normally this kiln was batch fed through cover doors on the side, but for the purposes of the coincineration experiments the sludge feed was accomplished through a water-cooled feed line which entered the kiln through the discharge pipe. The maximum feed rate was a nominal 45 kg/hr. Cake buildup within the kiln was prevented by 10 rows of link chain within the kiln [20].

The afterburner, with a residence chamber volume of 2.4 m^3, was fired by two 0.147-J/s throat mix burners and an auxiliary gas supply. The incinerator was equipped with a temperature controller and a high limit safety shutoff instrument. In this configuration, the maximum temperature that could be sustained was 1,260°C with residence times on the order of several seconds [20].

The multiple hearth test unit used for pesticide and PCB incineration contained the following components [15]:

- Waste feed system
- Multiple hearth incinerator
- Air pollution control device system

The PCB's in the form of a solution in kerosene were fed from a burette into the sludge cake feed screw at a rate of 22.5 g/hr. The test PCB was a preparation Aroclor 1254 which is a combination of some 14 to 16 PCB's [15].

The DDT feed was accomplished by a hopper arrangement placed over the screw-feed mechanism used to conduct the dewatered sludge from the centrifuge to the top hearth of the furnace. The mechanical properties of the powdered DDT preparation used were such that the simple gravity feed device was not particularly satisfactory; one might elect to go to a more elaborate vibratory feed system in practice. The feed device used did not effect a constant feed rate, a factor which was less serious than might be supposed [15].

The furnace was equipped with a scum line feeding into the third hearth. The injection of 2,4,5-T solution was accomplished by gravity feeding the metered solution into the scum flow. Incinerating temperature was 635°C and afterburner temperature was 650°C [15].

Types of Wastes -

The type of incinerator used in coincineration dictates the limitations on types of hazardous wastes which may be disposed.

Advantages -

(1) Will potentially incinerate any thermally destructible hazardous waste.
(2) Incorporates the advantages of the type of incinerator used.
(3) Provides for the incineration of two different wastes simultaneously in the same facility, thus increasing return on investment.
(4) Provides potential for hazardous waste incineration in existing incineration facilities.

Disadvantages -

(1) Incorporates the disadvantages of the type of incineration used.

2.3.2 Emerging Incineration Technology

This section deals with a technology that is in a research and development stage. It is not currently a recommended technique for hazardous waste disposal.

2.3.2.1 Starved Air Combustion/Pyrolysis [3, 6, 8, 10, 19, 25]--

Operation -

The terms "starved air combustion" and "pyrolysis," while often used interchangeably, are not one and the same. Starved air combustion uses less than the stoichiometric amount of oxygen required for complete combustion. Pyrolysis is defined as the thermal decomposition of a compound in the absence of oxygen. Figure 2-17 shows a schematic for a device utilizing starved air combustion/pyrolysis.

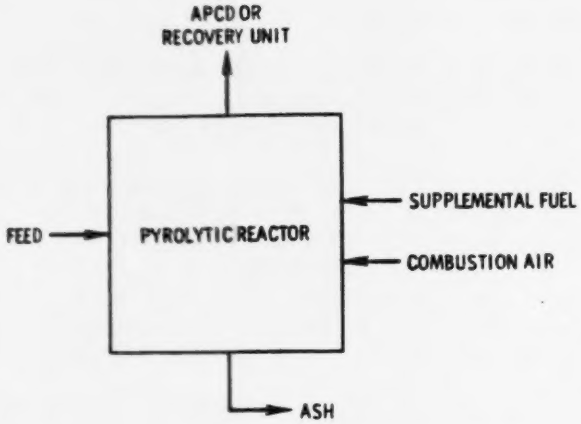


Figure 2-17. Starved air combustion/pyrolysis schematic.

Pyrolytic conversion processes are generally custom engineered according to input volumes and types of waste being treated. With respect to waste carbonaceous material, pyrolysis represents a means of converting the unwanted waste into a usable commodity with economic value. Modifications to the pyrolysis process involve treatment of converter effluents. The pyrolysis oils may be sent through a hydrotreating unit and converted to industrial fuel oil. The pyrolysis effluent gas may be cooled and the resultant condensate separated into its components (namely, acetic acid, methanol, furfural, acetone, butyric acid, propionic acid, methyl ethyl ketone, light fuel oil, and other water soluble volatile organics) through the use of conventional separation techniques. The cooled wet gas may be dried and utilized as fuel gas. The charlike pyrolysis residue can be further treated and converted into activated carbon [1].

Other variations include the pyrolyzer itself, which may be incorporated into a specific incinerator unit (i.e., rotary kiln, molten salt, etc.). A typical rotary kiln pyrolyzer, for instance, is a sealed, airtight retort cylinder with an insulated shell. The retort is mounted on a slight incline and rotates. Without oxygen, the wastes in the retort chamber cannot burn; they are broken down (pyrolyzed) into steam, carbon oxides, volatile vapors, and charcoal. Gases formed during pyrolysis are combusted in an afterburner.

Operational temperatures will vary with waste type, incinerator type, and desired products. Operating temperatures are usually in the 650°C ± 150°C range, with the lower operating temperature generally resulting in greater residue (coke), tar, and light oil yields, and lower gas yields. Residence times will range from a fraction of a second (for flash pyrolysis) to hours (for solids) [1].

Types of Wastes -

The general types of hazardous waste which are potential candidates for this technology are all physical forms of compounds having carbon, hydrogen, and/or oxygen. Wastes containing nitrogen, sulfur, sodium, silicon, phosphorous, fluorine, bromine, chlorine, or iodine aren't acceptable.

Advantages -

(1) Potential for byproduct recovery.
(2) Reduction of sludge volume without large amount of supplementary fuel.
(3) Thermal efficiency is higher than for normal incineration due to the lower quantity of air required for this process.
(4) Reduced air emissions are sometimes possible.
(5) Converts carbonaceous solids into a gas which is more easily combustible.
(6) Allows for the suppression of particulate emissions.
(7) Allows for some treatment of the hot fuel gas stream prior to combustion to suppress the formation of acid gases.

Disadvantages -

(1) Potential source of carcinogenic decomposition product formation.
(2) Not capable of functioning very well on sludge-like or caking material alone unless cake-breaking capabilities are included in the design.

2.3.3 Air Pollution Control Devices

The products of combustion in any well-designed and operated incinerator are primarily carbon dioxide and water (vapor), but trace amounts of undesirable additional products (pollutants) are also formed, depending upon the composition of the incinerated waste. Among these, CO, SO_x, NO_x, HX^1_1, X^1_2, and particulate are most commonly encountered and must be minimized to the point of emission standards outlined in Part 264 of RCRA [7].

An optimum pollution control process serves to minimize fuel usage, and/or maximize energy recovery, while converting an industrial waste into an environmentally acceptable form. This section looks at how such emission control processes are selected for various incineration technologies.

Application of air pollution control processes depends on operating characteristics of the components or devices, the physical/chemical characteristics of the waste to be treated, and the emission standards imposed by government regulations. In addition to the use of standard treatment devices of both the dry control and wet control methods (Table 2), the control of air pollutants with off-gas cleaning systems is the subject of rapidly developing technologies.

As each new generation process or device is introduced, it is evaluated and employed where warranted by the fast-developing state of the art [7].

Organic pollutants emitted as a result of incomplete combustion of waste material are often present in effluents from the primary combustion chamber at low concentration levels well under the lower flammability limit. The control of the emission of these organic pollutants can be handled by continued combustion at high temperatures using afterburners (also termed secondary combustion chambers).

Scrubbers are also used to control pollutant emissions. They operate by removing pollutants from the gas stream instead of changing the pollutants, as afterburners do. Afterburners and four types of scrubbers are covered in this section, as are electrostatic precipitators (ESP) and wet electrostatic precipitators (WEP). The subsections presented for each control device include operating principles, status with hazardous waste incinerators, suitable waste streams, advantages, and disadvantages.

2.3.3.1 Afterburner--

Afterburners are simple combustion chambers (incinerators) designed to improve destruction efficiencies. As a first step to an air pollution control process, the afterburner acts to continue the combustion process and greatly decrease pollutants in the flue gas. This in turn creates less pollutant loading on downstream emission control devices which require less servicing and maintenance, and produce less residue as a result. Figure 2-18 shows a basic afterburner flow scheme.

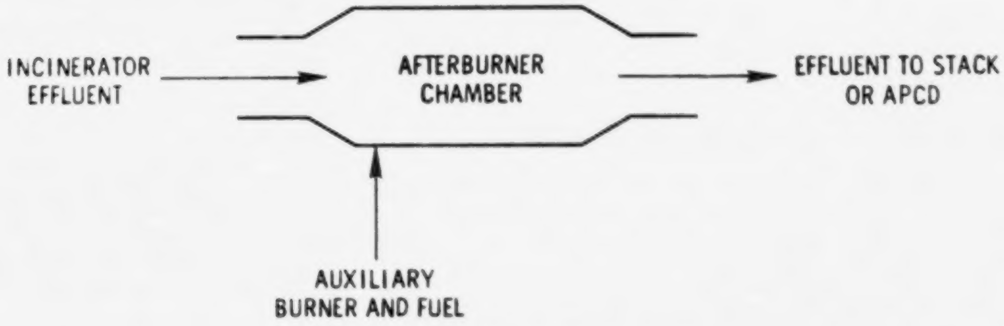


Figure 2-18. Basic afterburner flow scheme.

Three types of afterburners are discussed here: direct flame, thermal, and catalytic. Direct flame and thermal use a similar principle in thermally destroying combustible material. Direct flame afterburners pass the flue gas directly through a burning fuel stream, while thermal afterburners involve the flue gas flowing through a high temperature zone. Catalytic units incorporate a catalytic surface to accelerate the oxidation of uncombusted gas constituents.

Thermal afterburners are used more predominantly than direct flame incinerators. Temperatures ranging from 650°C to 1,300°C are generally required for successful operation of these devices. Hydrocarbon levels can usually be satisfactorily reduced at temperatures below about 760°C, but higher temperatures may be required to simultaneously oxidize the CO. The following temperatures are often used as guidelines [5]:

To oxidize hydrocarbons: 500 - 700°C
To oxidize carbon monoxide: 700° - 800°C

Depending on the type of pollutant in the gas stream, residence times ranging from 0.2 s to 6.0 s are required for complete combustion. The residence time in most practical afterburner systems is dictated primarily by chemical kinetic considerations. To ensure good mixing, afterburners are operated at high velocity gas flows. Gas velocities in afterburners range from 8 to 15 m/s. A typical afterburner will be 10 m long, 4 m high, and 4 m wide [5].

From a chemical viewpoint, two main types of reactions occur in afterburner systems: oxidation and pyrolysis reactions. In general, the detailed mechanisms for the oxidation and pyrolysis of even the simplest organic compounds are not completely understood, but it is well established that the reactions occur in many complicated sequential and concurrent steps involving a multitude of chemical intermediates [5].

An auxiliary fuel is fired to supply the heat to warm the gases to a temperature that will promote oxidation of the organic vapors. Usually a portion of the gas stream supplied the oxygen necessary for organic vapor oxidation.

Both gaseous and liquid fuels are used to fire afterburners. Gaseous fuels have the advantage of permitting firing in multiple jet (or distributed) burners. Oil firing has the disadvantage of producing sulfur oxides (from sulfur in the oil) and normally produces higher nitrogen oxides emissions [5].

Catalytic afterburners are applied to gaseous wastes containing low concentrations of combustible materials and air. Usually noble metals such as platinum and palladium are the catalytic agents. A catalyst is defined as a material which promotes a chemical reaction without taking a part in it. The catalyst does not change nor is it used up. However, it may become contaminated and lose its effectiveness [1].

The catalyst must be supported in the hot waste gas stream in a manner that will expose the greatest surface area to the waste gas so that the combustion reaction can occur on the surface, producing nontoxic effluent gases of carbon dioxide, nitrogen, and water vapor. Most of the combustion occurs during flow through the catalyst bed which operates at maximum temperatures of 810°C to 870°C. The ability to carry out combustion at relatively low temperatures while achieving high destruction efficiencies is a major advantage of the catalytic incinerator for gaseous wastes [1].

Residence time for catalytic oxidation is about 1 second [1].

Due to the form of the waste material to be treated (dilute and in the gaseous state), the catalytic afterburner is best suited for use at the processing site where the waste material is generated [1].

Generally, catalytic afterburners are considered for operation with waste containing hydrocarbon levels that are less than 25% of the lower explosice limit. When the waste gas contains sufficient heating value to cause concern about catalyst burnout, the gas may be diluted by atmospheric air to ensure operating temperatures within the operating limits of the catalyst. Burned gases are discharged through a stack to the atmosphere if they are not sent to a waste heat recovery unit [6].

Applicable Waste Streams - Thermal afterburners are suitable for any gaseous material that is also suitable for incineration or which has been produced by auxiliary equipment; i.e., a rotary kiln. Catalytic afterburners are applicable to the destruction of combustible materials in low concentrations (they are not applicable to chlorinated hydrocarbons due to the HCl formation).

Advantages -

Thermal or Direct Flame

(1) Destroys those pollutants that were not destroyed in the primary incineration.
(2) Allows more flexibility in incinerator operation.

Catalytic

(1) Carries out combustion at relatively low temperatures (more economical to operate than other afterburners).
(2) Clean heated gas produced is well suited for waste heat recovery units.

Disadvantages -

Thermal or Direct Flame

(1) Auxiliary fuel requirements.
(2) Afterburner costs.

Catalytic

(1) Burnout of the catalyst occurs at temperatures exceeding 815°C.
(2) Catalyst systems are susceptible to poisoning agents, activity suppressants, and fouling agents.
(3) Occasional cleaning and eventual replacement of catalyst is required.
(4) Maintenance costs are high.

2.3.3.2 Gas-Atomized Spray Scrubber (Venturi)--

One of the most predominant air pollution control devices for hazardous waste incinerators is a venturi scrubber (Figure 2-19). A typical venturi scrubber is a duct with a constricted area (throat). Generally, liquid is introduced into the venturi at the throat. Incinerator exhaust gas enters the venturi at

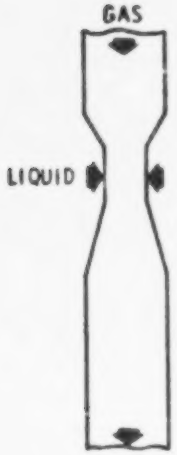


Figure 2-19. Venturi scrubber schematic.

a velocity of approximately 30 to 120 m/s. The moving gas atomizes the liquid into fine filaments and droplets which allow a large surface area for mass transfer. It is the gas/liquid contact that permits removal of gaseous contaminants.

Prior to passage of the incinerator exhaust gas into the venturi, the gas is quenched to reduce the temperature. While it is recognized that the quench systems when utilized will effect some degree of particle removal, the primary function of these units is to reduce flue gas volume and downstream materials and operating problems through gas cooling. As a result of quenching, inlet temperatures for venturi scrubbers range from 60°C to 150°C.

Some hazardous waste incineration facilities employ sequential venturi and plate type or packed bed scrubbers. For these systems, a gas quench is optional since the venturi may be utilized to effect gas cooling by the mechanism of adiabatic expansion of the gases. Such systems are capable of handling a variety of incineration gas compositions and dust loadings. Plate towers or packed beds, when used in conjunction with gas-atomized spray scrubbers, serve the dual function of eliminating the entrainment of liquid droplets from upstream and further reducing the emission levels of gaseous contaminants.

Incinerating hazardous waste may produce effluent gases with corrosive contaminants, such as HCl. It is possible to neutralize the acid with a caustic solution. The scrubbing solution is determined by the waste burned and its exhaust gas. In addition to corrosion, erosion is a particular problem in venturi scrubbers. This is due to the high gas velocities and particulate loadings encountered during normal duty. Throat and elbow areas are generally subject to the most wear. Acid-resistant tile liners, polymeric liners, and Inconel 625 are often used for scrubber construction.

Venturi scrubbers have been used to control emissions of SO_2, HF, and HCl. Several of the primary operating parameters that will affect the removal of these gaseous contaminants are pressure drop, liquid-to-gas ratio, contact time, and gas flow rate. Pressure drops in venturi scrubbers for controlling gaseous emissions from incineration of hazardous wastes are typically in the 7.5 to 12.5-kPa water gage (WG) range [21]. It is necessary to use the correct pressure drop to ensure efficient removal. A higher than needed pressure drop will result in wasted energy; a lower than needed pressure drop will result in a lower removal efficiency. As a prime operating parameter, the pressure drop should be as low as possible yet yield the needed removal efficiency.

The liquid-to-gas ratio is a design and operating parameter of prime importance. It is needed in the determination of the scrubber diameter, and has an effect on the unit dimensions. Normal liquid-to-gas ratios for venturi scrubbers are 0.7 to 2.7 L/m^3 [21].

Higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. The contact time required for gas absorption is a function of the rate of mass transfer. The mass transfer rate, in general, is dependent upon four separate resistances: gas-phase resistance, liquid-phase resistance, chemical reaction resistance, and a solids dissolution resistance for scrubbing liquids containing solid reactants. For absorption of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, such as the absorption of HCl by caustic solution, the contact time required for 99% removal is extremely short (of the order of 0.4 to 0.6 s). The less reactive and less soluble pollutants require a longer contact time [21].

The rate at which a flue gas from waste incineration must be processed by a particle control device depends primarily on the waste composition, the quantity of excess combustion air used, the initial gas temperature, and the method(s) by which the gas has been cooled, if cooling is used. Hence these parameters, in conjunction with control device size or geometry, will dictate the velocity at which the gas will pass the particle collection elements [21].

It has been shown that the pressure drop across a venturi is proportional to the square of gas velocity and directly proportional to the liquid-to-gas ratio. Therefore, within limits, increasing gas velocity will result in increasing pressure drop, other parameters being equal [21]. Typical gas velocities employed commercially are 30 to 120 m/s. The low end of this range, 30 to 45 m/s, is typical of power plant applications, while the upper end of the range has been applied to lime kilns and blast furnaces [21].

Particle cut diameter (diameter of particles in which there is a 50% collection) is a frequently used parameter for describing the particle collection performance of venturi scrubbers. One reason for this is because plots of collection efficiency versus particle diameter tend to be rather steep in the region where inertial impaction is the predominant collection mechanism. High energy venturi scrubbers provide the highest wet scrubber efficiency with cut diameters in the 0.3 to 0.5 μm range [21].

Applicable Waste Streams - Suitable for particles, and fairly effective in removing noxious gases that are highly soluble (HCl, HF) or reactive with the scrubber solution (SO_2, NO_x, HCN).

Advantages -

(1) Simultaneous gas absorption and dust removal.
(2) Suitable for high temperature, high moisture.
(3) Particulate removal efficiency is high.
(4) Scaling not usually a problem.

Disadvantages -

(1) Corrosion and erosion problems.
(2) Dust is collected wet and the wastewater will have to be treated.
(3) Moderate to high pressure drop; large amount of energy needed.
(4) Requires downstream mist eliminator.

2.3.3.3 Packed Bed Scrubber--

Packed bed scrubbers are used in hazardous waste incineration facilities because of their high removal efficiency for gaseous emissions. Designed properly, a packed bed scrubber will remove >99% of the halogens from incinerator exhaust gases. The inherent nature of the design does not, however, allow for removal of particulates from exhaust gases with high particulate loadings. Unless prior treatment is used, this type of waste stream will cause clogging in the packed bed scrubber [21].

The packed bed scrubber is a vessel filled with packing material as shown in Figure 2-20. The scrubbing liquid is fed into the top of the vessel, with gas flowing in either a cocurrent, countercurrent, or crosscurrent mode. As the liquid flows through the bed, it wets the packing material and provides interfacial surface area for mass transfer with the gas phase [21].

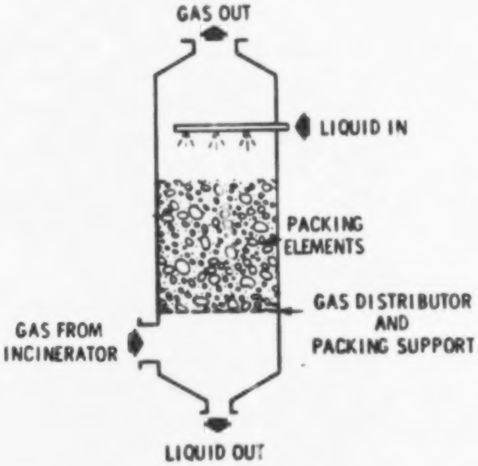


Figure 2-20. Packed bed scrubber schematic.

Differences between packed bed scrubbers include the flow mode, the packing material, and the depth of packing. The choice of flow mode is dependent upon the particular application. Crossflow scrubbing is generally applied to situations where the bed depth is less than 2 meters, and countercurrent design is applied at bed depths of 2 meters or more [21].

Packing material varies in shape and type. Shapes used include rings, spiral rings, and saddles. Packing materials are usually made of ceramic or some other material that will withstand corrosion from acids [21].

The primary parameters that affect scrubber design and the removal of gaseous emissions are discussed below. These include pressure drop, liquid-to-gas ratio, contact time, and gas flow rate [21].

Packed beds used for gaseous emission control in hazardous waste incineration facilities usually have a pressure drop range from 0.5 to 1.8 kPa. The total pressure drop across the packed bed is directly proportional to the depth of packing and affects the gaseous removal efficiency in the packed bed scrubber. Normal liquid-to-gas ratios in packed beds vary from 0.8 to 10 L/m^3, with most units operating between 3 and 7 L/m^3 [21].

In gas absorption devices, higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. Removal efficiencies for gaseous contaminants in packed beds are directly related to the depth of packing, which in turn determines the contact time [21].

The contact time required for gas absorption is a function of the rate of mass transfer. The mass transfer rate, in general, is dependent upon four separate resistances: gas-phase resistance, liquid-phase resistance, chemical reaction resistance, and a solids dissolution resistance for scrubbing liquids containing solid reactants [21].

In the design of gas absorption devices, the cross-sectional area for gas-liquid contact is determined by the superficial gas velocity selected. The greater the gas velocity selected, the smaller will be the scrubber diameter but the larger will be the pressure drop [21].

There are two additional factors to be considered in the selection of gas velocity. First, the gas velocity through the scrubber should allow sufficient residence time for gas-liquid contact. Second, in a countercurrent packed bed, the gas velocity should not exceed the flooding velocity. At the flooding point, the pressure-drop-versus-gas-rate curve becomes almost vertical, and a liquid layer starts to build up on top of the packing. The flooding poing represents the upper limiting conditions of pressure drop and fluid rates for practical tower operation (Figure 2-21). A margin of 30% to 40% of the flooding velocity should be allowed in designing these scrubber types. The most common gas velocities in packed beds range from 2.1 to 3.0 m/s [21].

As in the case with other wet scrubbers, mist eliminators are often used downstream of the packed bed scrubber for proper pollution control. When a wet scrubber follows or precedes a packed scrubber, mist eliminators are often not

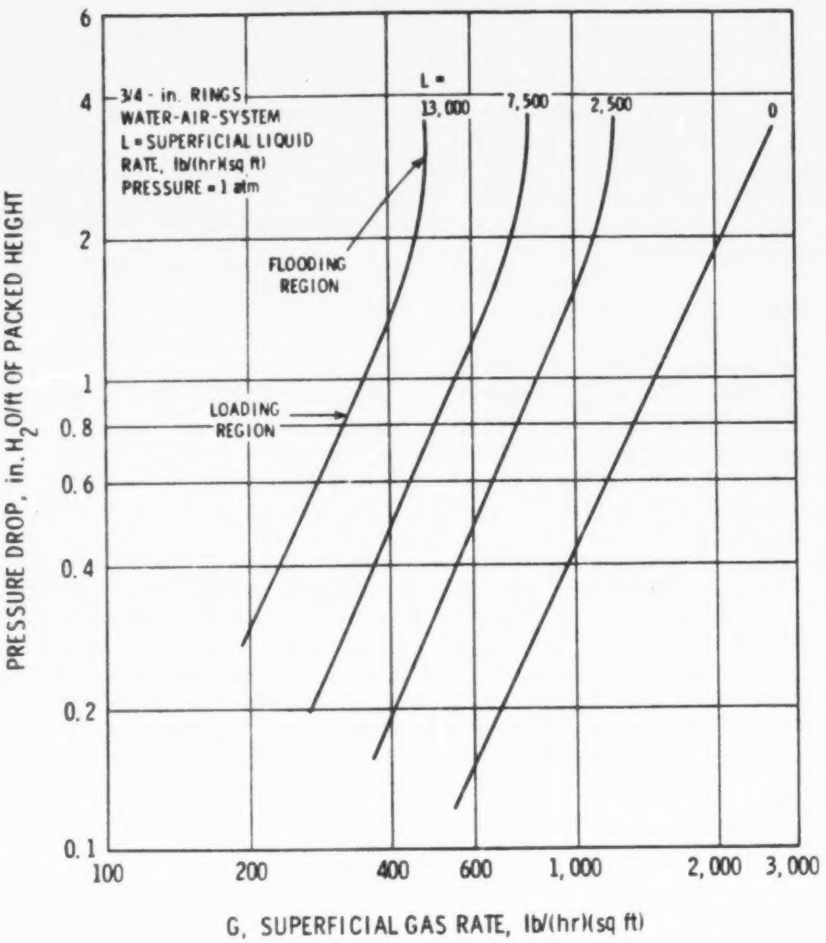


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Figure 2-21. Packed tower pressure drop as function of gas rate and liquid rate.

used. A packed bed scrubber is often sequential to a venturi in a hazardous waste incineration facility.

Most commonly, packed scrubbers are used with liquid injection incinerators because of the low particulate loading in the exhaust gas. The particulates in gas streams tend to clog up the bed and decrease removal efficiency. When packed beds are used to control gaseous emissions from rotary kilns and fluidized bed incinerators, venturi scrubbers are usually incorporated upstream as the primary APCD.

Applicable Waste Streams - Most suitable for the removal of noxious gases in streams containing low or no particulate loading.

Advantages -

(1) High removal efficiency for gaseous and aerosol pollutants.
(2) Low to moderate pressure drop.
(3) Engineering principles controlling the performance of packed bed scrubbers are well developed and understood.
(4) Availability of corrosion-resistant packings to withstand corrosive materials.

Disadvantages -

(1) Low efficiency for fine particles.
(2) Not suitable for high temperature or high dust loading applications.
(3) Requires downstream mist eliminator.
(4) Potential scaling and fouling problems.
(5) Possible damage to the scrubber if scrubber solution pumps fail.

2.3.3.4 Spray Tower--

Preformed spray towers are chambers in which a liquid is atomized by high pressure spray nozzle. The gas stream usually enters the bottom of the chamber and flows countercurrent to the liquid, although both cocurrent and cross-current modes have been used. The gas may travel in a single path (as in Figure 2-22) or may be directed by a series of baffles. The atomized liquid forms droplets and mass transfer occurs at the droplet surface. The finer the droplets, the more gas absorption is enhanced. Impurities which are soluble in the scrubbing liquid are removed by the gas absorption process.

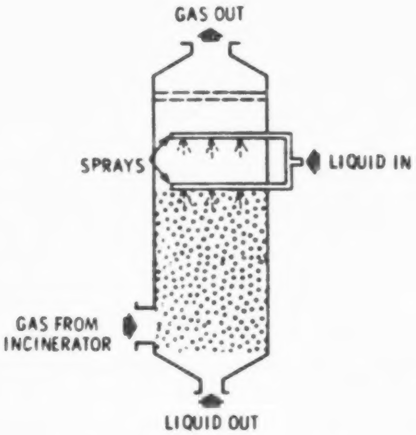

Figure 2-22. Spray tower schematic.

Several of the primary operating parameters that will affect the removal of gaseous contaminants in preformed towers are discussed here. These include the pressure drop, liquid-to-gas ratio, contact time, and gas flow rate. A normal pressure drop for a preformed spray tower is 0.125 to 0.996 kPa WG [21].

Liquid-to-gas ratios are strongly dependent upon the control device and the specific application. Under normal operating conditions, preformed spray towers employ liquid-to-gas ratios in the range of 4 to 14 L/m^3 [22].

In gas absorption devices, higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. The contact time required for gas absorption is a function of the rate of mass transfer. The mass transfer rate, in general, is dependent upon four separate resistances: gas-phase resistance, liquid-phase resistance, chemical reaction resistance, and a solids dissolution resistance for scrubbing liquids containing solid reactants. For absorption of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, such as the absorption of HCl by caustic solution, the contact time required for 99% removal is extremely short (of the order of 0.4 to 0.6 s). The rate at which flue gas from a waste incinerator must be processed by a particle control device depends primarily on the waste composition, the quantity of excess combustion air used, the initial gas temperature, and the method(s) by which the gas has been cooled, if cooling is used. Hence these parameters, in conjunction with the control device size or geometry, will dictate the velocity at which the gas will pass the particle collection elements. Because inertial impaction is the principal particle collection mechanism it is beneficial to operate with a high relative velocity between the gas and the collection element. Practical relative velocity limitations occur as a result of the increased operating costs associated with high pressure drops, flooding, or other considerations. The most common gas velocities in spray towers range from 2.1 to 3.0 m/s [21].

Applicable Waste Streams - Spray towers are suitable for gas streams with particles and gaseous pollutants.

Advantages -

(1) Simultaneous gas absorption and dust removal.
(2) Suitable for high temperature, high moisture, and high dust loading applications.
(3) Simple design.
(4) Rarely have problems with scaling.

Disadvantages -

(1) High efficiency may require high pump discharge pressures.
(2) Dust is collected wet.
(3) Nozzles are susceptible to plugging.
(4) Requires downstream mist eliminator.
(5) Structure is large and bulky.
(6) Lower particulate collection efficiency than a high pressure venturi.
(7) Lower absorption efficiency than a packed tower.

2.3.3.5 Plate Scrubber--

Plate scrubbers, like all wet scrubbers, remove gaseous contaminants in a gas absorption process that depends on intimate gas/liquid contact. The basic design of a plate scrubber is a vertical cylindrical column with a number of plates or trays inside as in Figure 2-23. Each plate has openings which can

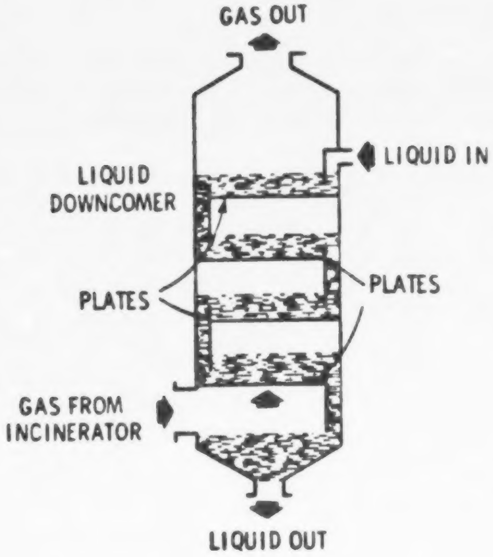

Figure 2-23. Plate tower schematic.

be in the form of perforations or slots. The scrubbing liquid is introduced at the top plate and flows across it, then down to the next plate. A downcomer, located on alternate sides of each successive plate, permits the downward movement of the liquid. The scrubbing liquid exits along with the pollutants at the liquid outlet located at the tower bottom.

Incinerator gas enters the bottom of the tower and passes up through the plate openings before exiting at the top. The gas has enough velocity to prevent the liquid from flowing through the holes in the plates. Gas absorption is promoted by the breaking up of the gas phase into little bubbles which pass through the volume of liquid in each plate.
At hazardous waste incineration facilities, plate towers with two sieve trays are typically used as an absorber/mist eliminator in conjunction with a high energy venturi scrubber.

The primary operating parameters that will affect the removal of gaseous contaminants such as SO_2 are discussed here. These include the pressure drop, liquid-to-gas ratio, contact time, and gas flow rate.

Total pressure drop across the plate towers is similar to that of packed beds and in the 0.5 to 1.8 kPa WG range. In plate towers pressure drop is not used as an operating parameter to estimate removal efficiency. Rather, the number of plates is the primary parameter that determines removal efficiency [21].

The liquid-to-gas ratio is a design and operating parameter of prime importance. It is needed in the determination of the scrubber diameter, and has an effect on the height of a transfer unit. A high liquid-to-gas ratio will lead to the requirement of a larger diameter, but at the same time will also reduce the height of a transfer unit. Normal liquid-to-gas ratios in plate towers vary from 0.8 to 10 L/m^3 with most units operating at between 3 and 7 L/m^3 [21].

Higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. Greater depths of liquid on the trays lead to higher tray efficiency through longer contact time. An increase in the number of plates and the column height also improves removal efficiency.

In the design of gas absorption devices, the cross-sectional area for gas-liquid contact is determined by the superficial gas velocity selected. The greater the gas velocity selected, the smaller will be the scrubber diameter but the larger will be the pressure drop.

There are two additional factors that must be considered in the selection of gas velocity. First, the gas velocity through the scrubber should allow sufficient residence time for gas-liquid contact. Second, in countercurrent plate towers, the gas velocity should not exceed the flooding velocity (the upper limiting conditions of pressure drop and fluid rates for practical operation). A margin of 30% to 40% of the flooding velocity should be allowed in designing these scrubber types. The most common gas velocities in plate towers, range from 2.1 to 3.0 m/s.

Parameters that affect the particle collection performance of a plate scrubber include pressure drop, liquid-to-gas ratio, gas velocity, dust loading, and particle size distribution. High particulate loadings and fine particles are unfavorable conditions.

Plate towers are appropriate when particle size is not less than 1μm. Unlike absorption efficiency, particle collection efficiency will not necessarily improve with an increased number of plates, but decreased perforation diameter does increase particle collection efficiency. The other parameters have been discussed previously and will not be addressed [22].

Applicable Waste Streams - Most suitable for the removal of noxious gases with low particulate loadings.

Advantages -

(1) Simultaneous gas absorption and dust removal.
(2) High removal efficiency for gaseous and aerosol pollutants.
(3) Low to moderate pressure drop.
(4) Mass transfer increases with multiple plates.
(5) Handles high liquid rates.

Disadvantages -

(1) Low efficiency for fine particles.
(2) Not suitable for high temperature or high dust loading applications.
(3) Requires downstream mist eliminator.
(4) Limestone scrubbing solution causes scaling.
(5) Not suitable for foamy scrubbing liquid.

2.3.3.6 Electrostatic Precipitator (ESP)--
Electrostatic precipitation is a process by which particles suspended in a gas are electrically charged and separated from the gas stream. In this process, shown in Figure 2-24, negatively charged gas ions are formed between emitting and collecting electrodes by applying a sufficiently high voltage to the emitting electrodes to produce a corona discharge. Suspended particulate matter is charged as a result of bombardment by the gaseous ions and migrates toward the grounded collecting plates due to electrostatic forces. Particle charge is neutralized at the collecting electrode where subsequent removal is effected by periodically rapping or rinsing. A majority of industrial EPS's used today are the single-stage, wire and plate type; charging and collection take place in the same section of the ESP. Two-stage ESP;s, often called electrostatic filters, utilize separate sections for particle charging and collecting, and are not generally employed for controlling particulate emissions from combustion sources.

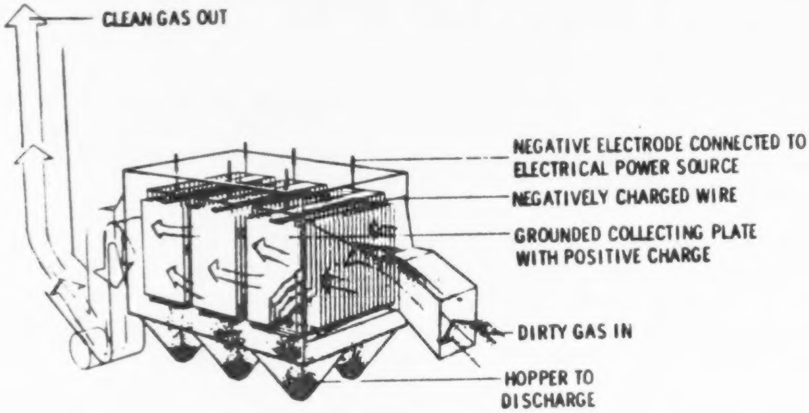
CLEAN GAS OUT
NEGATIVE ELECTRODE CONNECTED TO ELECTRICAL POWER SOURCE
NEGATIVELY CHARGED WIRE
GROUNDED COLLECTING PLATE WITH POSITIVE CHARGE
DIRTY GAS IN
HOPPER TO DISCHARGE

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Figure 2-24. Electrostatic precipitator schematic.

charge is neutralized at the collecting electrode where subsequent removal is effected by periodically rapping or rinsing. A majority of industrial EPS's used today are the single-stage, wire and plate type; charging and collection take place in the same section of the ESP. Two-stage ESP;s, often called electrostatic filters, utilize separate sections for particle charging and collecting, and are not generally employed for controlling particulate emissions from combustion sources.

Electrostatic precipitators have been widely used in conjunction with utility boilers and with municipal and industrial incinerators. ESP's have been employed by European facilities where hazardous wastes are incinerated, although the wastes generally do not contain highly chlorinated compounds. When halogenated wastes are incinerated, careful waste blending is employed to protect ESP's from corrosion, so that HCl concentrations do not exceed 1,000 ppm and usually average 300 ppm [23]. Dry ESP's are not capable of removing acid gases and, therefore, facilities burning halogenated wastes must employ two-stage gas cleaning if ESP's are used for particulate emission control.

ESP components that are in direct contact with the process gas stream include the shell, electrodes, high voltage frames, rapper rods and gas distribution plates. On the basis of mild steel construction, such components constitute approximately 68% of the total precipitator weight and account for 45% of the total unit cost [23]. Hence, the applications requiring exposure to corrosive gas streams have substantial impact on ESP design and ultimate cost. Lead linings, used in acid mist ESP's, are not generally suitable for use in incinerator gas treatment due to poor resistance to attack by gaseous halogens. Fiber glass reinforced plastic (FRP) has been successfully utilized for inlet and outlet plenums as well as collecting electrodes; however, the latter application requires provision of adequate conductivity to permit current flow to ground.

ESP's are carefully designed and constructed for maximum electrical safety; however, normal high voltage precautions must be observed. Design features such as interlocks between access doors and electrical elements should be employed. Also, access after deenergizing should be delayed to allow for static charge drainage.

Compared to those of wet scrubbers, pressure and temperature drops across ESP's are very small. The pressure drop across an ESP is typically below 0.25 kPa WG as compared with wet scrubbers which may operate with pressure drops up to 15 kPa WG. Additionally, ESP's provide generally higher removal efficiencies for particles smaller than 1 μm in diameter than do wet scrubbers. A standard gas temperature range is up to 370°C and the voltage normally applied ranges from 30 kV to 75 kV.

Applicable Waste Streams - Effective for the collection of fine particles (less than 1 μm in diameter), but unable to capture noxious gases. Performs poorly on particles with high electrical resistivity.

Advantages -

(1) Dry dust collection.
(2) Low pressure drop and operating cost.
(3) Efficient removal of fine particles.
(4) Collection efficiency can be improved when stream is treated (i.e., highly conducting dust treated with SO_2).

Disadvantages -

(1) Relatively high capital cost.
(2) Sensitive to changes in flow rate.
(3) Particle resistivity affects removal and economics.
(4) Not capable of removing gaseous pollutants.
(5) Fouling potential with tacky particles.

2.3.3.7 Wet Electrostatic Precipitator (WEP)--

The wet electrostatic precipitator (Figure 2-25) is a variation of the dry electrostatic precipitator design. The two major added features in a WEP system are: (1) a preconditioning step, where inlet sprays in the entry section are provided for cooling, gas absorption, and removal of coarse particles, and (2) a wetted collection surface, where liquid is used to continuously flush away collected materials. Particle collection is achieved by introduction of evenly distributed liquid droplets to the gas stream through sprays located above the electrostatic field sections, and migration of the charged particles and liquid droplets to the collection plates. The collected liquid droplets from a continuous downward-flowing film over the collection plates, and keep them clean by removing the collected particles. To control the carryover of liquid droplets and mists, the last section of the WEP is often designed so that mists can be collected on baffles [24].

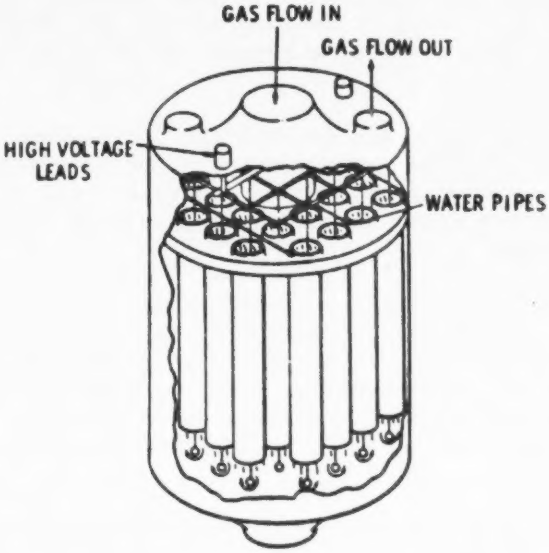

Figure 2-25. Wet electrostatic precipitator schematic.

The WEP overcomes some of the limitations of the dry electrostatic precipitator. The operation of the WEP is not influenced by the resistivity of the particles. Further, since the internal components are continuously being washed with liquid, buildup of tacky particles is controlled and there is some capacity for removal of gaseous pollutants. In general, applications of the WEP fall into two areas: removal of fine particles, and removal of condensed organic fumes. Outlet particulate concentrations are typically in the 2 to 24 mg/m^3 range [24].

Data on capability of the WEP to remove acid gases are very limited. WEP's have been installed to control HF emissions from Soderberg aluminum reduction cells [23]. With a liquid-to-gas ratio of 0.67 L/m^3 and a liquid pH between 8 and 9, fluoride removal efficiencies higher than 98% have been measured. Outlet concentration of HF was found to be less than 1 ppm.

There are no WEP installations at hazardous waste incineration facilities. A potential application is to consider use of the WEP in conjunction with a low pressure drop venturi scrubber upstream, where a major portion of the gaseous contaminants and heavy particles will be removed. The WEP will then serve as a second stage control device for removal of the submicron particles and remaining gaseous pollutants. Because of its limited application history, extensive pilot testing prior to design and installation may be necessary [24].

Applicable Waste Stream - Effective in removal of fine particles and of condensed organic fumes.

Advantages -

(1) Simultaneous gas absorption and dust removal.
(2) Low energy consumption.
(3) No dust resistivity problems.
(4) Efficient removal of fine particles.

Disadvantages -

(1) Low gas absorption efficiency.
(2) Sensitive to changes in flow rate.
(3) Dust collecton is wet.

2.3.4 Heat Recovery Technology

As Section 2.3.1 on incinerator technology in hazardous waste incineration pointed out, temperatures during incineration may range up to 1600°C. The flue gas from such a process has a substantially high heating value, especially if the volumetric flow rate is great. Some form of waste heat recovery is beneficial at any rate.

Three basic types of waste heat recovery are possible in any incineration process. These include gas-to-water, gas-to-air, and gas-to-organic fluid [7].

Since steam has a tremendous heat energy per unit weight, gas-to-water systems producing steam are the most commonly used heat recovery systems. This steam in turn is generally used as a power source in other site processes. Steam generation is usually accomplished by directing flue gases immediately from the last incineration step into a heat recovery boiler. A simple version of this heat exchange process is included in Figure 2-26. Gas flow may be regulated, usually by a damper, to control the amount of heat recovery. This system, depending on the volume and temperature of the flue gas, can act as the primary or secondary source of process steam when combined with a conventional boiler system.

Gas-to-air systems are also commonly used heat recovery systems, usually using heated air as combustion air in the incineration process. The same heat exchange principle as in gas-to-water is practiced in heating air. Heating of combustion air lessens the need for auxilliary combustion fuel, as the temperature of the air-waste-fuel mixture is much closer to the waste's oxidation point. Research is also being done to determine the value of heating air for use in power generation.

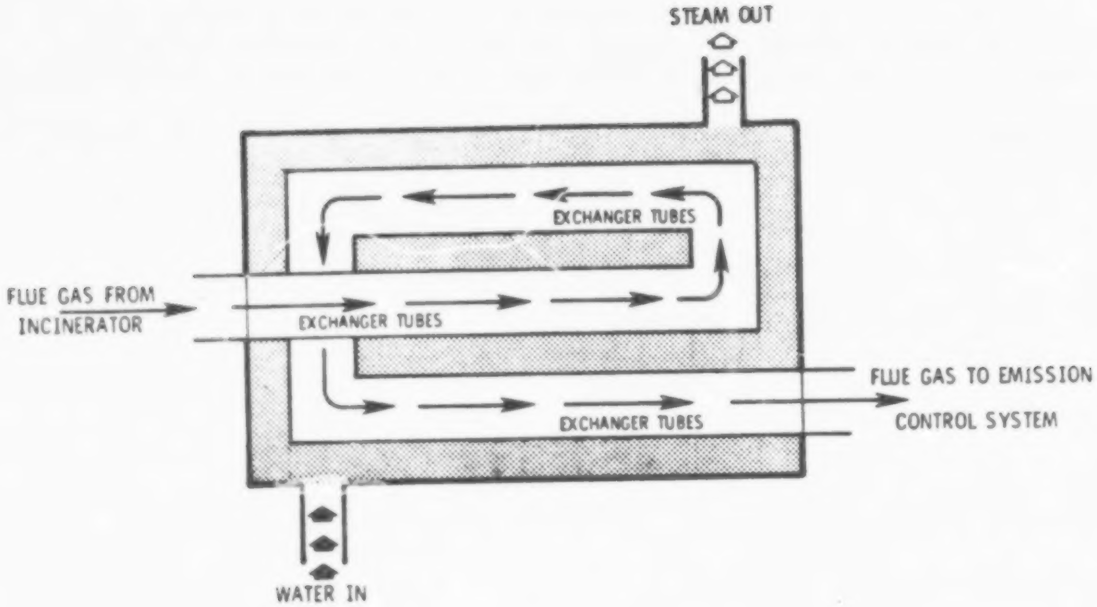

Figure 2-26. Heat recovery/gas-to-water

Gas-to-organic fluid heat exchange also uses a heat exchange principle outlined in Figure 2-26. This process can be used in heating mineral oil or ethylene glycol, which is in turn used in controlling temperatures of additional processes [7].

2.4 FOREIGN TECHNOLOGIES

2.4.1 Introduction

Foreign incinerators are basically the same as found in the United States. The rotary kiln is widely used for the simultaneous incineration of solid, liquid, and semisolid wastes of all calorific values. In addition, the fixed firebox/muffle furnace is used for liquid and/or gaseous wastes; fluidized bed, multiple chamber, and liquid injection incinerators are utilized less frequently. Heat recovery is incorporated into hazardous waste incineration systems more frequently than in the United States.

In nearly all waste-to-energy combustion units, energy is recovered through production of steam, either with classic fire-tube boilers or newer waterwall boilers. Some combustion units do without a boiler and use the hot combustion gases directly. Coincineration of municipal wastes and selected hazardous wastes is a common practice in a number of foreign countries, particularly the Netherlands. Countries with strict environmental legislation are more likely to segregate hazardous wastes for treatment in separate facilities. Selected hazardous waste incineration technologies of Canada, Japan, and Germany are discussed in the following three sections. Table 2-6 presents a partial listing of industrial waste facilities outside the United States.

TABLE 2-5. TECHNOLOGIES APPROPRIATE FOR HAZARDOUS WASTE INCINERATION

			Thermal oxidation			Heat recovery		Temperature regulation		
Physical form	Hazardous industrial waste	Pollutant	Rotary kiln	Liquid injection	After-burner	Heat recovery boiler	Heat exchanger	Quench chamber	Cooling tower	Off-gas recycle
Gas	Asphalt fumes		x		x	x	x			x
	Chloroform	Cl_2/HCl	x		x			x		
	Hydrocarbon fumes		x		x	x	x			x
	HCN and H_2	NO_x	x			x		x		
	H_2S vents	SO_x	x		x	x		x		
	Methyl chloride	Cl_2/HCl	x		x			x		
	NH_3	NO_x	x			x		x		
	NO_x	NO_x	x			x		x		
	Phosgene	Cl_2/HCl	x		x			x		
	Tail gas		x		x	x	x			x
	VCM[a] vents	Cl_2/HCl	x		x			x		
Gas/solid	Air/maleic anhydride		x		x	x	x			x
	Air/phthalic anhydride		x		x	x	x			x
	Air/polyethylene		x		x	x	x			x
	CO and H_2/C		x		x	x	x			x
	CO, H_2/C and ash	Particulate	x		x	x		x	x	x
	Hydrocarbon/C and ash	Particulate	x		x	x		x	x	x
	Propene/Al_2O_3	Particulate	x		x	x		x	x	x
Liquid	Acrylonitrile	NO_x	x	x	x	x		x		
	Carbon tetrachloride	Cl_2/HCl	x	x	x			x		
	Chloroamine	Cl_2/HCl, NO_x	x	x	x			x		
	Herbicides	Cl_2/HCl	x	x	x			x		
	Hexachlorobenzene	Cl_2/HCl	x	x	x			x		
	Hydrazine	NO_x	x	x		x		x		

(continued)

TABLE 2-5 (continued)

Physical form	Hazardous industrial waste	Pollutant	Air pollution control device						
			Reduction furnace	Venturi scrubber	Caustic absorber	Wet scrubber	Cyclone	Electrostatic precipitator	Bag-house
Gas	Asphalt fumes								
	Chloroform	Cl_2/HCl			X	X			
	Hydrocarbon fumes								
	HCN and H_2	NO_x	X						
	H_2S vents	SO_x			X	X			
	Methyl chloride	Cl_2/HCl			X	X			
	NH_3	NO_x	X						
	NO_x	NO_x	X						
	Phosgene	Cl_2/HCl			X	X			
	Tail gas								
	VCM[a] vents	Cl_2/HCl			X	X			
Gas/solid	Air/maleic anhydride								
	Air/phthalic anhydride								
	Air/polyethylene						X		
	CO and H_2/C						X		
	CO, H_2/C and ash	Particulate		X		X	X	X	X
	Hydrocarbon/C and ash	Particulate		X		X	X	X	X
	Propene/Al_2O_3	Particulate		X		X		X	X
Liquid	Acrylonitrile	NO_x	X						
	Carbon tetrachloride	Cl_2/HCl			X	X			
	Chloroamine	Cl_2/HCl, NO_x	X		X	X			
	Herbicides	Cl_2/HCl			X	X			
	Hexachlorobenzene	Cl_2/HCl			X	X			
	Hydrazine	NO_x	X						

(continued)

TABLE 2-5 (continued)

Physical form	Hazardous industrial waste	Pollutant	Thermal oxidation			Heat recovery		Temperature regulation		
			Rotary kiln	Liquid injection	After-burner	Heat recovery boiler	Heat exchanger	Quench chamber	Cooling tower	Off-gas recycle
	H_2O and creosote		X	X	X	X	X			
	H_2O and isocyanates		X	X	X	X	X			
	Nitrosamine	NO_x	X	X						
	Organic acids		X	X	X	X	X			X
	Pesticides	Cl_2/HCl	X	X	X	X		X		X
	PCB	Cl_2/HCl	X	X	X	X		X		X
	Pyridine	NO_x	X	X				X		
	VCM[a]	Cl_2/HCl	X	X	X			X		
	High N_2 crude	NO_x	X	X		X		X		X
Solid	APPA[b]/catalyst	Particulate	X		X	X			X	X
	Coal fines	Particulate	X			X			X	
	Coke fines	Particulate	X			X			X	
	DMT cellulose	NO_x	X			X			X	
	Polyethylene		X			X	X			
	Sodium organic salts	Particulate	X			X			X	
	Wood chips	Particulate	X			X			X	X
Liquid/solid	APPA[b] and solvent/catalyst	Particulate	X	X	X	X			X	
	Biosludge	Particulate	X			X			X	
	Dye solution	Particulate	X	X		X			X	X
	Melamine slurry	NO_x	X			X		X	X	
	Phosphorus sludge	H_3PO_4	X							
	Salt solution	Particulate	X	X		X			X	
	TPA[c]/catalyst	Particulate	X	X	X	X			X	
	Polypropylene/catalyst	Particulate	X	X	X	X			X	

(continued)

TABLE 2-5 (continued)

Physical form	Hazardous industrial waste	Pollutant	Air pollution control device: Reduction furnace	Venturi scrubber	Caustic absorber	Wet scrubber	Cyclone	Electrostatic precipitator	Bag-house
	H_2O and creosote								
	H_2O and isocyanates								
	Nitrosamine	NO_x	X						
	Organic acids								
	Pesticides	Cl_2/HCl			X	X			
	PCB	Cl_2/HCl			X	X			
	Pyridine	NO_x	X						
	VCM[a]	Cl_2HCl			X	X			
	High N_2 crude	NO_x	X						
Solid	APPA[b]/catalyst	Particulate	X					X	X
	Coal fines	Particulate		X			X	X	X
	Coke fines	Particulate		X			X	X	X
	DNT cellulose	NO_x	X				X		
	Polyethylene						X		
	Sodium organic salts	Particulate		X			X	X	X
	Wood chips	Particulate		X			X	X	X
Liquid/solid	APPA[b] and solvent/catalyst	Particulate		X				X	X
	Biosludge	Particulate		X				X	X
	Dye solution	Particulate		X				X	X
	Melamine slurry	NO_x	X						
	Phosphorous sludge	H_3PO_4		X					
	Salt solution	Particulate		X				X	X
	TPA[c]/catalyst	Particulate		X				X	X
	Polypropylene/catalyst	Particulate		X				X	X

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[a] Vinyl chloride monomer.

[b] 0,0-Dimethyl-phthalimidiomethyl-dithiophosphate.

[c] Phorbol acetate, myristate.

TABLE 2-6. SELECTED INDUSTRIAL WASTE INCINERATION FACILITIES IN EUROPE AND JAPAN

Plant	Country	Start-up	Waste to be treated	Capacity Gcal/h	furnace	recovery
BASF Ludwigshafen	Germany	1960	solid industrial waste	15	G	s
Boehringer Pharma Ingelheim	Germany	1962	solid chemical waste, timber, waste paper, garbage	2	G	none
Opel Bochum	Germany	1963	waste paper, timber, plastic, garbage, waste paint	4	G	none
BASF Ludwigshafen	Germany	1964	solid, semi-solid and liquid chemical waste, waste oil, waste paint, solvents	7.2	K	s
Continental Hannover	Germany	1964	carbon black, waste paper, rubber, grease, waste oil	7.5	G	s
Opel Russelsheim	Germany	1966	waste paper, timber, plastic garbage, waste paint	6.2	G	s
Chemical Works Huls Marl	Germany	1966	solid, semi-solid and liquid chemical waste, carbon black, rubber, timber	12	K	s
Explosives factory Dottikon	Switzerland	1969	acid sludge, distillation residues, waste oil, activated carbon, waste paper, timber	3.2	H	none
Alfa Sud Pomigliano (Naples)	Italy	1973	waste paper, timber, plastic, garbage, waste paint	4	G	none
Kobe Steel Kobe	Japan	1974	waste oil, grease, plastic, timber, rubber, waste paint	4	K	none
Kommune Kemi Nyborg	Denmark	1975	solid, semi-solid and liquid industrial waste	20	K	s h H
Gelsenberg-Mannesmann Umweltschutz Bochum	Germany	1976	waste oil, solvents, slurries, pumpable chemical waste	30	M	s e E
Kobe Steel Kakogawa	Japan	1976	waste oil, grease, plastic, timber, rubber, waste paper	1.8	K	none
Denki Kagaku Ohmi	Japan	1977	tar, plastic, rubber, waste oil, slurries	1.1	K	none
Entsorgungsbetriebe Simmering Vienna	Austria	1980	sewage sludge solid, semi-solid and liquid industrial waste	14.5 25.8	F K	s h e H s h e H
Hessische Industriemull Biebesheim	Germany	1980	solid, semi-solid and liquid industrial waste	15	K	H e
Svensk Avfallskonvertering Norrtorp	Sweden	1981	solid, semi-solid and liquid industrial waste	17.4	K	s h e E

Explanation of symbols:

Type of furnace

G = Grate furnace
K = Rotary kiln
H = Hearth-type furnace
F = Fluidized bed furnace
M = Melting chamber

Kind of heat recovery

s = Steam for internal use
S = Steam for sale
h = Hot water for internal use
H = Hot water for sale
e = Electric power for internal use
E = Electric power for sale

2.4.2 Canada - [25, 26, 27, 32]

There are two regional incineration facilities with a possible third in the planning stage. All are privately owned and financed. Licensing of these facilities is the responsibility of the government of the provinces in which the incinerators are located. Conventional methods for treatment and disposal of hazardous wastes generated by the petroleum and organic chemical industries have proven inadequate for the volume of such wastes. Experimental programs to determine the feasibility of utilizing a cement kiln for destruction of hazardous wastes have been conducted by the Environmental Protection Service of Canada under partial sponsorship of the U.S. Environmental Protection Agency.

The use of cement kilns for the disposal of waste liquids was recommended in Canada at first in 1974 in a report issued by Environment Canada. It was suggested to use cement kilns for the disposal of waste oil, thereby recovering the heat value of the oil and as well as retaining the inorganic constituents of the oil in cement clinker.

An extensive series of experimental waste oil burns was conducted in the spring of 1974. The result verified that the emissions of toxic substances to the atmosphere were negligible, and there were no adverse effects on cement quality. Heavy metal contaminants were chemically combined into the lattice structure of the cement in a manner similar to the glazing of pottery.

Severe temperature conditions required for the thermal destruction of other hazardous wastes, such as chlorinated hydrocarbons, are customarily maintained in the cement kiln. In addition, hydrochloric acid and calcium chloride are added to the cement kiln feed for purposes of alkali reduction.

The use of kilns for the destruction of chlorinated hydrocarbon wastes containing up to 46% (by weight) chlorine was investigated in joint U.S. - Canada incineration tests. The waste used included a variety of chlorinated hydrocarbons in the series of program phases designed to progress from easily combusted chlorinated hydrocarbons (chlorinated aliphatics) to those which are combusted with difficulties (chlorinated aromatics and alicyclics). The last phase consisted of 50-100 percent polychlorinated biphenyl wastes.

The results of the stack gas sampling analyses indicated a minimum combustion efficiency of the waste feed to be 99.986%, and although traces of volatile low molecular weight hydrocarbons were found (approximately 50 ppb), there was no evidence of the existence of polychlorinated biphenyls at the limits of detection of the methods and procedures, 3 micrograms per cubic meter.

It was concluded in early 1976 that cement kilns could be a viable alternative for the destruction of liquid hazardous wastes and in fact an approval or license was issued to a Canadian cement works. But it may be added that the public was totally and completely unaware of these investigations, and specifically of the positive results. When it became generally known that this company was handling PCB's, the public reaction was swift and intensive, and finally so effective that the company voluntarily surrendered back to the provincial agency, its license for PCB disposal. Therefore at present no PCB's are burned.

The Canadian experience with the use of cement kilns has spanned five years. It has proven that cement kilns represent an environmentally secure system for the destruction of liquid chlorinated hydrocarbons if they are properly equipped, operated, and regulated. But it has also shown that introducing a new waste disposal method for hazardous wastes means involving the public at an early stage of the development, such that their concerns could be recognized, and the appropriate answers developed in a rational and scientific manner.

2.4.3 Japan [24, 26, 31]

The rotary kiln is the incinerator most commonly used in Japan. Takuma Boiler Manufacturing Company designed a continuous synthetic polymer waste disposal plant for destruction of PVC products. A rotary kiln is used in this system for pretreatment of PVC products under dry distillation conditions. PVC products are dry distilled at about 300°C; when air is excluded this produces HCl. After HCl is vaporized from the resin material, the carbonized resin materials are burned in the incinerators (the same way as other techniques). The HCl gas from the rotary kiln passes through a multi-cyclone and a gas cooler. It is then reacted with ammonia gas to produce ammonium chloride, separated, collected by a dust collector, and finally carried away by a conveyor to a storage point.

Kawasaki Heavy Industries utilize fluidized bed incinerators for the burning of liquid plastic wastes. Recently, this type of incinerator has been used for drying various kinds of chemicals in many industries. For further information on the operation of fluidized beds consult Section 2.3.3.3.

The FLK process has been developed by Ebara Infilco Company incorporating equipment invented by Dr. Johannes Wotchke and currently in use at Volkswagenwerk of West Germany for destruction of defective automobile tires (at the rate of 250 per hour). The Ebara FLK process incorporates the small flame chamber (FLK) incinerator for complete high temperature incineration (up to 1500°C). The process can be used to burn either solid wastes (such as tires or high-polymer plastics) or liquids (such as waste oils or solvents).

Emission control technologies utilized in Japan and other countries are those in use in the United States - the spray tower, centrifugal spray scrubber, venturi scrubber, electrostatic precipitator, and cyclone.

2.4.4 West Germany [25, 28, 29, 32]

West Germany has the most stringent environmental emission standards in Western Europe, yet incineration is the preferred method for disposal of certain hazardous industrial wastes. Co-incineration is seldom conducted since the method of disposal of industrial waste is determined by government regulation. Waste oil, plastics, solvents, and other wastes of organic origin can be incinerated with or without chemical or physical pretreatment. Five incinerator technologies are used for the destruction of most hazardous wastes:

(1) rotary kilns and burn-out chambers
(2) fluidized bed kiln
(3) combustion chamber kiln
(4) turbulator action kiln
(5) grate kiln

The general rules for the application of these kiln types are:

(1) Rotary kiln: the most versatile kiln for all kinds of waste in solid, pasty, or liquid condition. Very flexible by distribution of the liquid waste feed between rotary kiln head and secondary combustion chamber.

(2) Fluidized bed kiln: for pasty and liquid wastes like sludges and effluents from refineries, petrochemical plants, and water purification plants; flexible for fluctuating throughput rates and wastes of varying composition. Wastes with low calorific value need a support firing.

(3) Combustion chamber with special nozzles: for effluents with low calorific value to be used where the expensive fluidized-bed kiln is not necessary.

(4) Turbulator: a high-temeprature combustion chamber with turbulent gas flow for liquid wastes with high calorific value. Due to special refractory lining it can stand great thermal loads.

Suitable for pyrolysis and breaking-up of metal chlorides. Due to high gas velocities, solids and dust are carried over. Therefore the off-gas cleaning is very important.

(5) Grate: types utilized in incinerators with longitudinal overthrust grates and rotating basket grates, mostly in combination with steam boiler systems.

A description of the operation of the Bavarian regional hazardous waste disposal plant follows*:

The central plant has a laboratory to check all incoming wastes and to distribute them to the proper storage and treatment areas.

The annual capacity is approximately 100,000 t/year of solid, pasty, and liquid residues with a mean calorific value of 3,300 kcal/kg. The thermal capacity is 25 Gcal/h. It is processed in two parallel rotary kilns having one common after-burner chamber. The plant is designed for adding a third kiln some time in the future.

Bunkers for the solids have a capacity of 900 m^3. They are controlled by a crane operator from a stationary location.

For pasty residues 4 steam-heated bunkers of 100 m^3 capacity each are provided.

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*Reference 28.

The tank yard for liquid wastes has a total storage capacity of 200 m^3. Beside it is located the barrel melting cabinet.

Each rotary kiln can handle either 5 t/h solids with a net calorific value of 2500 Kcal/kg, or 3.1 t/h pasty wastes with a net calorific value of 4000 Kcal/kg, or any combination which does not exceed 12.5 Gcal/h.

The afterburner chamber handles the off-gases from:

(1) 2 rotary kilns without burning additional liquids, or
(2) 1 rotary kiln and in addition 2.4 t/h liquid wastes with a net calorific value of 5200. These liquids are burned in the side walls.

The vertical gas velocity is 3.5 m/s in the afterburner chamber at a thermal load of 25 Gcal/h.

The off-gas at a rate of 66,000 Nm^3/h leaves the afterburner chamber at a temperature of 1000°C.

Heat is recovered in a steam boiler. The gases leave the boiler at 270°C. Steam is generated at 25 atm and superheated to 250°C at a rate of 34 t/h.

A steam turbine generates electric power at the rate of 1320 kw/h consuming 22 t/h steam. The remainder is condensed in an air condenser. This electric energy is sufficient to supply the entire plant's demand requirements. The steam from the turbine - 3 atm - is utilized for heating the building and for process heat in the central plant.

The off-gas is cleaned with high efficiency by an electrostatic precipitator followed by a two-stage radial flow scrubber. Dust, HCl, and HF are nearly completely removed; SO_2 removal is on the order of 70 percent. The scrubbing liquid is circulated at a rate of 150 m^3/h. Since 2 m^3/h are discharged to keep the concentration at a constant value, and 10 m^3/h are vaporized in the two scrubber stages, some 12 m^3/h fresh water is supplied to the system. The discharged water carries sludge from the neutralizing agents and is further processed in the central plant. The saturated off-gases are reheated before leaving the stack to avoid condensation of the gas stream. This is accomplished in a heat exchanger and by addition of preheated air before the gases are exited to the stack.

The gases leaving the stack are almost completely free from toxic ingredients. They consist of nitrogen, oxygen, CO_2, and H_2O as they normally exist in the atmosphere.

Slag and ashes are deposited at a selected sanitary landfill and constitute approximately 1/10th of the original volume of the materials charged.

The Bavarian incineration facility was designed to comply with stringent West German environmental regulations. Ownership of the plant is shared by industry and municipal and state governments.

2.5 INCINERATOR MANUFACTURERS

This section lists vendors of various types of hazardous waste incinerators. The listing does not necessarily include all manufacturers of hazardous waste incineration equipment. It should also be noted that inclusion in this list does not guarantee that the organization listed is currently a supplier of hazardous waste incineration equipment, nor does it represent an endorsement of any such equipment manufacturer by EPA.

The following list (Table 2-7) of vendors was taken from an EPA-sponsored report and represents only manufacturers who were willing to provide the additional information shown. For the most part, names, addresses, and some phone numbers were obtained from one or more listings in four current vendor directories. These directories include:

(1) 1981 Chemical Engineering Catalog.
(2) February 1981 Buyers' Guide, Solid Waste Management Magazine.
(3) 1981 Catalog and Buyers' Guide, Pollution Equipment News (Nov. 1980, Vol. 13, #6).
(4) 1980-81 Directory and Resource Book, Air Pollution Control Association.

A later report [33] estimated that, of the 340 hazardous waste incinerators in service, 219 are liquid injection, 57 are fixed hearth (controlled air), 42 are rotary kiln (primarily cocurrent), and the remaining 22 are of several modified and other types of designs.

TABLE 2-7. HAZARDOUS WASTE INCINERATOR VENDORS

Air Resources
600 N. First Bank Dr.
Palatine, IL 60067
(312) 359-7810

Basic Environmental Engineering, Inc.
21 W. 161 Hill Avenue
Glen Ellyn, IL 60137
(312) 469-5340

Baumco, Inc.
Pittsburgh, PA 15219
(412) 216-3555

Bayco Industries of California
2108 Davis Street
San Leandro, CA 94577
(415) 562-6700

Bigelow-Liptak Corp.
21201 Civic Center Drive
Southfield, MI 48076
(313) 353-5400

Brule C.E.&E., Inc.
13920 Southwestern Avenue
Blue Island, IL 60406
(312) 388-7900

C. E. Raymond Co.
Bartlett-Snow Division
200 West Monroe Street
Chicago, IL 60606
(312) 236-4044

CICO, Inc.
1600 W. Haskell
Appleton, WI 54911
(414) 734-9861

Coen Company
Burlingame, CA
(415) 697-0440

Commercial Fabrication & Machine Co., Inc.
P.O. Box 472
Mount Airy, NC 27030
(919) 786-8374

(continued)

TABLE 2-7 (continued)

Copeland Associates, Inc.
125 Windsor Dr.
Oak Brook, IL 60521
(312) 986-8564

Dorr Oliver, Inc.
Stamford, CT 06904
(203) 358-3676

Ecologenics Corp.
P.O. Box 348
Red Lion, PA 17356
(717) 244-8549

Econo-Therm Energy Systems Corp.
11535 K-Tel Drive
Minnetonka, MN 55343
(612) 938-3100

Enercon Systems, Inc.
16115 Puritas Avenue
Cleveland, OH 44135
(216) 267-0555

Energy, Inc.
Idaho Falls, ID 83401
(208) 529-1000

Entech Industrial Systems, Inc.
The Woodlands, TX 77380
(713) 353-2319

Environmental Control Products, Inc.
11100 Nations Ford Road
P.O. Box 15753
Charlotte, NC 28210
(704) 588-1620

Environmental Elements Corp.
(Sub. of Koppers Co., Inc.)
Baltimore, MD 21203
(301) 796-7334

Fuller Co.
Bethlehem, PA
(215) 264-6011

(continued)

TABLE 2-7 (continued)

Fuller Co.
Bethlehem, PA
(215) 264-6011

HPD, Inc.
Glen Ellyn, IL 60137
(312) 357-7330

Hirt Combustion Engineers
931 South Maple Avenue
Montebello, CA 90640
(213) 728-9164

Industronics, Inc.
489 Sullivan Ave.
P.O. Drawer G
S. Windsor, CT 06074
(203) 289-1551

International Incinerators, Inc.
P.O. Box 19
Columbus, GA 31902
(404) 327-5475

John Zink Co.
Tulsa, OK 74105
(918) 747-1371

Kelley Co., Inc.
6720 N. Teutonia Avenue
Milwaukee, WI 53207
(414) 352-1000

Met-Pro Corporation, Sys. Div.
160 Cassell Rd.
P.O. Box 144
Harleysville, PA 19438
(215) 723-6751

Midland-Ross Corp.
2275 Dorr Street
Toledo, OH 43691
(419) 698-4341

Morse Boulger, Inc.
53-09 97th Pl.
Corona, NY 11368

(continued)

TABLE 2-7 (continued)

Peabody International Corp.
4 Landmark Sq.
Stamford, CT 06901
(203) 327-7000

Plibrico
1800 N. Kingsbury Avenue
Chicago, IL 60614
(312) 549-7014

Prenco, Inc.
29800 Stephenson Hwy.
Madison Heights, MI 48071
(313) 399-6262

Pyro Magnetics Corp.
200 Essex Street
P.O. Box 288
Whitman, MA 02382
(617) 447-0448

Shirco, Inc.
2451 Stemmons Hwy.
Dallas, TX 75207
(214) 630-7511

Sunbeam Equipment Corp.
Comtro Division
180 Mercer Street
Meadville, PA 16335
(814) 724-1456

Sure-Lite Corp.
Santa Fe Springs, CA 90670
(213) 693-0796

TR Systems, Inc.
239 Commerce Street
So. Windsor, CT 06033
(203) 528-3728

Tailor & Co., Inc.
P.O. Box 587
Davenport, IA 52805
(319) 355-2621

(continued)

TABLE 2-7 (continued)

Thermal Processes, Inc.
507 Willow Springs Road
La Grange, IL 60525
(312) 747-6600

Trane Thermal Co.
Conshohocken, PA 19428
(215) 828-5400 (x45)

Trofe, Inc.
Pike Road
Mt. Laurel, NJ 08054
(609) 235-3036

United Corporation
1947 N. Topeka Blvd.
Topeka, KS 66608
(913) 232-2349

U.S. Smelting Furnace Co.
C.E. Industries Corp.
Belleville, IL
(618) 233-0129

Vulcan Iron Works, Inc.
United Penn Bank Bldg., Room 1050
Wilkes Barre, PA 18701
(717) 822-2161

The Washburn & Granger, Inc.
85 5th Avenue
P.O. Box 304
Patterson, NJ 07524
(211) 278-1965

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CHAPTER 3

WASTE CHARACTERIZATION

3.1 INTRODUCTION

Waste characterization is a major factor in assessing the feasibility of destroying a hazardous waste material by incineration. It affects the design of the incinerator and its emissions control system and helps determine the compatibility of a waste with a proposed or available facility. It also plays a part in determining incinerator operating conditions for complete destruction of a specific waste.

This chapter discusses the importance of the physical, chemical, and thermodynamic properties of hazardous wastes in evaluating them for incineration and in selecting a compatible incineration technology type. It also classifies RCRA Section 3001 hazardous wastes and other hazardous wastes as good, potential, or poor candidates for incineration, based on technical considerations, and identifies compatible incineration technology types for these wastes. In addition, it presents information on sampling and analysis of hazardous wastes for characterization, and it provides a work sheet to help in evaluating a waste for incineration.

3.2 WASTE CHARACTERIZATION BACKGROUND INFORMATION

Background information about the hazardous waste(s) is generally available. Such information may have been generated under Section 3001 (Identification and Listing of Hazardous Waste), Section 3002 (Standards Applicable to Generators of Hazardous Waste), or Section 3003 (Standards Applicable to Transporters of Hazardous Waste) of the RCRA regulations. Additional information can usually be obtained from studies of the process(es) generating the waste(s). This background information is helpful in evaluating waste for incineration.

3.2.1 Information Available from Waste Generators

A generator of hazardous waste should be able to provide the Standard Industrial Classification (SIC) code of the industry from which the waste originates, the EPA hazardous waste number, and a short description of the waste. The generator may also provide a detailed description of the process that generates the waste.

3.2.2 Information Available from Transporters

Federal or state regulations regarding transportation of the waste may give additional waste characterization information. The manifest that accompanied a waste shipment will identify the waste hazard class according to DOT regulations. Also, waste data sheets (forms) that are used prior to discharge of any waste at a disposal operation may be available. These types of information are helpful in evaluating a waste or planning provisions for personnel and environmental safety during storage and handling of the waste at the facility.

3.2.3 Additional Information Sources

Additional information relevant to hazardous waste incineration can be obtained by contacting the following sources:

A. EPA regional offices:

Region I
John F. Kennedy Federal Building
Room 2203
Boston, MA 02203
Telephone: (617) 223-7210

Region II
26 Federal Plaza, Room 1009
New York, NY 10007
Telephone: (212) 264-2525

Region III
Curtis Building
6th & Walnut Streets
Philadelphia, PA 19106
Telephone: (215) 597-9814

Region IV
345 Courtland Street, NE
Atlanta, GA 30308
Telephone: (404) 881-4727

Region V
230 S. Dearborn Street
Chicago, IL 60604
Telephone: (312) 353-2000

Region VI
First International Building
1201 Elm Street
Dallas, TX 75270
Telephone: (214) 767-2600

Region VII
1735 Baltimore Street
Kansas City, MO 64108
Telephone: (816) 374-5493

Region VIII
1860 Lincoln Street
Denver, CO 80203
Telephone: (303) 837-3895

Region IX
215 Fremont Street
San Francisco, CA 94105
Telephone: (415) 556-2320

Region X
1200 6th Avenue
Seattle, WA 98101
Telephone: (206) 442-1220

B. Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
5555 Ridge Avenue
Cincinnati, OH 45268
Telephone: (513) 684-4303

C. Office of Solid Waste
U.S. Environmental Protection Agency
401 M Street, SW
Washington, DC 20460
Telephone: (202) 755-9206

D. State Environmental Protection Departments

Table 3-1 can also be consulted relative to RCRA Section 3001 hazardous wastes and other hazardous wastes which are good, potential, or poor candidates for incineration with appropriate incineration technologies, based on technical considerations. This table was prepared using available background documents for some of the listed waste, trial burn data, and engineering judgment based on chemical formula(s) of compound(s) present in the waste. The following criteria were used to structure engineering judgment:

Waste containing	Incineration category
· Carbon, hydrogen, and/or oxygen	Good
· Carbon, hydrogen, ≤30% by weight chlorine and/or oxygen	Good
· Carbon, hydrogen, and/or oxygen, >30% by weight chlorine, phosphorus, sulfur, bromine, iodine, or nitrogen	Potential
· Unknown percent of chlorine	Potential
· Inorganic compounds	Poor
· Compounds containing metals	Poor

Other factors to be considered in evaluating waste for incineration are:

TABLE 3-1. HAZARDOUS WASTES RATED AS GOOD, POTENTIAL, OR POOR CANDIDATES FOR INCINERATION BY APPROPRIATE TECHNOLOGIES [1-8]

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Generic							
F001	The spent halogenated solvents used in degreasing, tetrachloroethylene, trichloroethylene, methylene chloride, 1,1,1-trichloroethane, carbon tetrachloride, and the chlorinated fluorocarbons; and sludges from the recovery of these solvents in degreasing operations.		√		√	√	√
F002	The spent halogenated solvents, tetrachloroethylene, methylene chloride, trichloroethylene, 1,1,1-trichloroethane, chlorobenzene, 1,1,2-trichloro-1,2,2-trifluoroethane, o-dichlorobenzene, trichlorofluoromethane and the still bottoms from the recovery of these solvents.		√		√	√	√
F003	The spent nonhalogenated solvents, xylene, acetone, ethyl acetate, ethyl benzene, ethyl ether, n-butyl alcohol, cyclohexanone, and the still bottoms from the recovery of these solvents.	√			√	√	√
F004	The spent nonhalogenated solvents, cresols and cresylic acid, nitrobenzene, and the still bottoms from the recovery of these solvents.	√			√	√	√
F005	The spent nonhalogenated solvents, methanol, toluene, methyl ethyl ketone, carbon disulfide, isobutanol, pyridine and the still bottoms from the recovery of these solvents.	√			√	√	√
F006	Wastewater treatment sludges from electroplating operations			√			
F007	Spent plating bath solutions from electroplating operations			√			
F008	Plating bath sludges from the bottom of plating baths from electroplating operations.			√			
F009	Spent stripping and cleaning bath solutions from electroplating operations.			√			
F010	Quenching bath sludge from oil baths from metal heat treating operations.			√			
F011	Spent solutions from salt bath pot cleaning from metal heat treating operations.			√			
F012	Quenching wastewater treatment sludges from metal heat treating operations.			√			
F013	Flotation tailings from selective flotation from mineral metals recovery operations.			√			
F014	Cyanidation wastewater treatment tailing pond sediment from mineral metals recovery operations			√			
F015	Spent cyanide bath solutions from mineral metals recovery operations			√			
F016	Dewatered air pollution control scrubber sludges from coke ovens and blast furnaces.			√			
Wood preservation							
K001	Bottom sediment sludge from the treatment of wastewaters from wood preserving processes that use creosote and/or pentachlorophenol		√			√	√
Inorganic pigments							
K002	Wastewater treatment sludge from the production of chrome yellow and orange pigments			√			
K003	Wastewater treatment sludge from the production of molybdate orange pigments			√			
K004	Wastewater treatment sludge from the production of zinc yellow pigments			√			

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration: Good	Candidate for incineration: Potential	Candidate for incineration: Poor	Incinerator type: Liquid injection	Incinerator type: Rotary kiln	Incinerator type: Fluidized bed
Inorganic pigments (cont'd)							
K005	Wastewater treatment sludge from the production of chrome green pigments			✓			
K006	Wastewater treatment sludge from the production of chrome oxide green pigments (anhydrous and hydrated)			✓			
K007	Wastewater treatment sludge from the production of iron blue pigments			✓			
K008	Oven residue from the production of chrome oxide green pigments			✓			
Organic chemicals							
K009	Distillation bottoms from the production of acetaldehyde from ethylene		✓				
K010	Distillation side cuts from the production of acetaldehyde from ethylene		✓				
K011	Bottom stream from the wastewater stripper in the production of acrylonitrile						
K012	Still bottoms from the final purification of acrylonitrile in the production of acrylonitrile		✓				
K013	Bottom stream from the acetonitrile column in the production of acrylonitrile	✓			✓	✓	✓
K014	Bottoms from the acetronitrile purification column in the production of acrylonitrile		✓				
K015	Still bottoms from the distillation of benzyl chloride		✓				
K016	Heavy ends or distillation residues from the production of carbon tetrachloride		✓		✓	✓	
K017	Heavy ends (still bottoms) from the purification column in the production of epichlorohydrin		✓			✓	✓
K018	Heavy ends from fractionation of ethyl chloride production		✓			✓	✓
K019	Heavy ends from the distillation of ethylene dichloride in ethylene dichloride production		✓			✓	✓
K020	Heavy ends from the distillation of vinyl chloride in vinyl chloride monomer production		✓			✓	✓
K021	Aqueous spent antimony catalyst waste from fluoromethanes production		✓			✓	✓
K022	Distillation bottom tars from the production of phenol/acetone from cumene			✓			
K023	Distillation light ends from the production of phthalic anhydride from naphthalene	✓				✓	✓
K024	Distillation bottoms from the production of phthalic anhydride from naphthalene		✓		✓	✓	✓
K025	Distillation bottoms from the production of nitrobenzene by the nitration of benzene		✓			✓	✓
K026	Stripping still tails from the production of methyl ethyl pyridines		✓				
K027	Centrifuge residue from toluene diisocyanate production		✓				
K028	Spent catalyst from the hydrochlorinator reactor in the production of 1,1,1-trichloroethane		✓				
K029	Waste from the product stream stripper in the production of 1,1,1-trichloroethane		✓	✓			

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration: Good	Candidate for incineration: Potential	Candidate for incineration: Poor	Incinerator type: Liquid injection	Incinerator type: Rotary kiln	Incinerator type: Fluidized bed
Organic chemicals (cont'd)							
K030	Column bottoms or heavy ends from the combined production of trichloroethylene and perchloroethylene		✓			✓	✓
Pesticides							
K031	By products salts generated in the production of MSMA and cacodylic acid			✓			
K032	Wastewater treatment sludge from the production of chlordane		✓				
K033	Wastewater and scrub water from the chlorination of cyclopentadiene in the production of chlordane		✓				
K034	Filter solids from the filtration of hexachlorocyclopentadiene in the production of chlordane			✓			
K035	Wastewater treatment sludges generated in the production of creosote		✓				
K036	Still bottoms from toluene reclamation distillation in the production of disulfoton		✓				
K037	Wastewater treatment sludges from the production of disulfoton		✓				
K038	Wastewater from the washing and stripping of phorate production		✓				
K039	Filter cake from the filtration of diethylphosphorodithoric acid in the production of phorate		✓			✓	✓
K040	Wastewater treatment sludge from the production of phorate			✓			
K041	Wastewater treatment sludge from the production of toxaphene		✓				
K042	Heavy ends or distillation residues from the distillation of tetrachlorobenzene in the production of 2,4,5-T		✓				
K043	2,6-Dichlorophenol waste from the production of 2,4-D		✓				
Explosives							
K044	Wastewater treatment sludges from the manufacturing and processing of explosives		✓			✓	✓
K045	Spent carbon from the treatment of wastewater containing explosives	✓				✓	✓
K046	Wastewater treatment sludges from the manufacturing, formulation and loading of lead-based initiating compounds			✓			
K047	Pink/red water from TNT operations	✓			✓	✓	✓
Petroleum refining							
K048	Dissolved air flotation (DAF) float from the petroleum refining industry	✓				✓	✓
K049	Slop oil emulsion solids from the petroleum refining industry	✓				✓	✓
K050	Heat exchanger bundle cleaning sludge from the petroleum refining industry		✓			✓	✓
K051	API separator sludge from the petroleum refining industry	✓				✓	✓
K052	Tank bottoms (leaded) from the petroleum refining industry		✓			✓	✓
Leather tanning finishing							
K053	Chrome (blue) trimmings generated by the following subcategories of the leather tanning and finishing industry; hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue; and shearling			✓			

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Leather tanning finishing (cont'd)							
K054	Chrome (blue) shavings generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue; and shearling			✓			
K055	Buffing dust generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; and through-the-blue			✓			
K056	Sewer screenings generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue; and shearling			✓			
K057	Wastewater treatment sludges generated by the following subcategories of the leather tanning and finishing industry; hair pulp/chrome tan/retan/wet finish, hair save/chrome tan/retan/wet finish; retan/wet finish; no beamhouse; through-the-blue and shearling			✓			
K058	Wastewater treatment sludges generated by the following subcategories of the leather tanning and finishing industry: hair pulp/chrome tan/retan/wet finish; hair save/chrome tan/retan/wet finish; and through-the-blue			✓			
K059	Wastewater treatment sludges generated by the following subcategory of the leather tanning and finishing industry: hair save/nonchrome tan/retan/wet finish			✓			
Iron and steel							
K060	Ammonia still lime sludge from coking operations			✓			
K061	Emission control dust/sludge from the electric furnace production of steel			✓			
K062	Spent pickle liquor from steel finishing operations			✓			
K063	Sludge from lime treatment of spent pickle liquor from steel finishing operations			✓			
Primary copper							
K064	Acid plant blowdown slurry/sludge resulting from the thickening of blowdown slurry from primary copper production			✓			
Primary lead							
K065	Surface impoundment solids contained in and dredged from surface impoundments at primary lead smelting facilities			✓			
Primary zinc							
K066	Sludge from treatment of process wastewater and/or acid plant blowdown from primary zinc production			✓			
K067	Electrolytic anode slimes/sludges from primary zinc production			✓			
K068	Cadmium plant leach residue (iron oxide) from primary zinc production			✓			

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Secondary lead							
K069	Emission control dust/sludge from secondary lead smelting			✓			
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof							
P001	3-(alpha-Acetonylbenzyl)-4-hydroxycoumarin and salts	✓			✓	✓	✓
P002	1-Acetyl-2-thiourea		✓		✓	✓	✓
P003	Acrolein	✓			✓	✓	✓
P004	Aldrin		✓			✓	✓
P005	Allyl alcohol	✓			✓	✓	✓
P006	Aluminum phosphide			✓			
P007	5-(Aminomethyl)-3-isoxazolol		✓			✓	✓
P008	4-Aminopyridine		✓			✓	✓
P009	Ammonium picrate		✓			✓	✓
P010	Arsenic acid			✓			
P011	Arsenic pentoxide			✓			
P012	Arsenic trioxide			✓			
P013	Barium cyanide			✓			
P014	Benzenethiol		✓		✓	✓	✓
P015	Beryllium dust			✓			
P016	Bis(chloromethyl) ether		✓		✓	✓	✓
P017	Bromoacetone		✓		✓	✓	✓
P018	Brucine	✓				✓	✓
P019	2-Butanone peroxide	✓			✓	✓	✓
P020	2-sec-butyl-4,6-dinitrophenol	✓			✓	✓	✓
P021	Calcium cyanide			✓			
P022	Carbon disulfide	✓			✓	✓	✓
P023	Chloroacetaldehyde		✓		✓	✓	✓
P024	p-Chloroaniline	✓				✓	
P025	1-(p-Chlorobenzoyl)-5-methoxy-2-methylindole-3-acetic acid	✓			✓	✓	
P026	1-(o-Chlorophenyl) thiourea		✓			✓	
P027	3-Chloropropionitrile		✓		✓	✓	
P028	alpha-Chlorotoluene	✓			✓	✓	
P029	Copper cyanide			✓			
P030	Cyanides			✓			
P031	Cyanogen	✓				✓	✓
P032	Cyanogen bromide		✓			✓	✓
P033	Cyanogen chloride		✓			✓	✓
P034	2-Cyclohexyl-4,6-dinitrophenol	✓				✓	✓
P035	2,4-Dichlorophenoxyacetic acid (2,4-D)		✓			✓	
P036	Dichlorophenylarsine			✓			
P037	Dieldrin	✓				✓	
P038	Diethylarsine			✓			
P039	O,O-Diethyl-S-[2-(ethylthio)ethyl] ester of phosphorothioic acid		✓		✓	✓	✓
P040	O,O-Diethyl-O-(2-pyrazinyl) phosphorothioate	✓			✓	✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration: Good	Candidate for incineration: Potential	Candidate for incineration: Poor	Incinerator type: Liquid injection	Incinerator type: Rotary kiln	Incinerator type: Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
P041	O,O-Diethyl phosphoric acid, O-p-nitrophenyl ester		✓		✓	✓	✓
P042	3,4-Dihydroxy-alpha-(methylamino)-methyl benzyl alcohol	✓			✓	✓	✓
P043	Di-isopropylfluorophosphate		✓		✓	✓	✓
P044	Dimethoate		✓			✓	✓
P045	3,3-Dimethyl-1-(methylthio)-2-butanone-O-[(methylamino)carbonyl] oxime		✓			✓	✓
P046	alpha, alpha-dimethylphenethylamine	✓			✓	✓	✓
P047	4,6-Dinitro-o-cresol and salts		✓			✓	✓
P048	2,4-Dinitrophenol		✓			✓	✓
P049	2,4-Dithiobiuret		✓			✓	✓
P050	Endosulfan		✓			✓	
P051	Endrin		✓		✓	✓	
P052	Ethylcyanide	✓			✓	✓	✓
P053	Ethylenediamine	✓			✓	✓	✓
P054	Ethyleneimine	✓			✓	✓	✓
P055	Ferric cyanide			✓			
P056	Fluorine			✓			
P057	2-Fluoroacetamide		✓			✓	✓
P058	Fluoroacetic acid, sodium salt			✓			
P059	Heptachlor		✓			✓	
P060	1,2,3,4,10,10-Hexachloro-1,4,4a,5,8,8a-hexahydro-1,4:5,8-endo, endo-dimethanonaphthalene		✓			✓	✓
P061	Hexachloropropene		✓		✓	✓	✓
P062	Hexaethyl tetraphosphate		✓			✓	✓
P063	Hydrocyanic acid	✓			✓	✓	✓
P064	Isocyanic acid, methyl ester	✓			✓	✓	✓
P065	Mercury fulminate			✓			
P066	Methomyl		✓			✓	✓
P067	2-Methylaziridine	✓			✓	✓	✓
P068	Methyl hydrazine	✓			✓	✓	✓
P069	2-Methyllactonitrile		✓		✓	✓	✓
P070	2-Methyl-2-(methylthio)propionaldehyde-o-(methylcarbonyl) oxime		✓			✓	✓
P071	Methyl parathion		✓			✓	✓
P072	1-Naphthyl-2-thiourea		✓			✓	✓
P073	Nickel carbonyl			✓			
P074	Nickel cyanide			✓			
P075	Nicotine and salts		✓			✓	✓
P076	Nitric oxide			✓			
P077	p-Nitroaniline		✓			✓	✓
P078	Nitrogen dioxide			✓			
P079	Nitrogen peroxide			✓			
P080	Nitrogen tetroxide			✓			
P081	Nitroglycerine	✓			✓	✓	✓
P082	N-Nitrosodimethylamine		✓			✓	✓
P083	N-Nitrosodiphenylamine		✓			✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
P084	N-Nitrosomethylvinylamine		✓			✓	✓
P085	Octamethylpyrophosphoramide		✓			✓	✓
P086	Oleyl alcohol condensed with 2 moles ethylene oxide	✓			✓	✓	✓
P087	Osmium tetroxide			✓			
P088	7-Oxabicyclo[2.2.1]heptane-2,3-dicarboxylic acid	✓			✓	✓	✓
P089	Parathion		✓		✓	✓	✓
P090	Pentachlorophenol		✓			✓	
P091	Phenyl dichloroarsine			✓			
P092	Phenylmercury acetate			✓			
P093	N-Phenylthiourea		✓			✓	✓
P094	Phorate		✓		✓	✓	✓
P095	Phosgene		✓			✓	✓
P096	Phosphine		✓			✓	✓
P097	Phosphorothioic acid, O,O-dimethyl ester, O-ester with N,N-dimethyl benzene sulfonamide		✓		✓	✓	✓
P098	Potassium cyanide			✓			
P099	Potassium silver cyanide			✓			
P100	1,2-Propanediol	✓			✓	✓	✓
P101	Propionitrile	✓			✓	✓	✓
P102	2-Propyn-1-ol	✓			✓	✓	✓
P103	Selenourea			✓			
P104	Silver cyanide			✓			
P105	Sodium azide			✓			
P106	Sodium cyanide			✓			
P107	Strontium sulfide			✓			
P108	Strychnine and salts		✓			✓	✓
P109	Tetraethyldithiopyrophosphate		✓			✓	✓
P110	Tetraethyl lead			✓			
P111	Tetraethylpyrophosphate		✓		✓	✓	✓
P112	Tetranitromethane		✓		✓	✓	✓
P113	Thallic oxide			✓			
P114	Thallium selenite			✓			
P115	Thallium (1) sulfate			✓			
P116	Thiosemicarbazide		✓			✓	✓
P117	Thiuram		✓			✓	✓
P118	Trichloromethanethiol		✓			✓	✓
P119	Vanadic acid, ammonium salt			✓			
P120	Vanadium pentoxide			✓			
P121	Zinc cyanide			✓			
P122	Zinc phosphide			✓			
U001	Acetaldehyde	✓			✓		
U002	Acetone	✓			✓	✓	✓
U003	Acetonitrile		✓		✓	✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration: Good	Candidate for incineration: Potential	Candidate for incineration: Poor	Incinerator type: Liquid injection	Incinerator type: Rotary kiln	Incinerator type: Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U004	Acetophenone	✓			✓	✓	✓
U005	2-Acetylaminoflourene		✓			✓	✓
U006	Acetyl chloride		✓		✓	✓	✓
U007	Acrylamide		✓			✓	✓
U008	Acrylic acid	✓			✓	✓	✓
U009	Acrylonitrile	✓			✓	✓	✓
U010	6-Amino-1,1a,2,8,8a,8b-hexahydro-8-(hydroxymethyl)8-methoxy-5-methylcarbamate azirino(2',3':3,4) pyrrol0(1,2-a)indole-4, 7-dione (ester)		✓			✓	✓
U011	Amitrole		✓			✓	✓
U012	Aniline	✓			✓	✓	✓
U013	Asbestos			✓			
U014	Auramine		✓			✓	✓
U015	Azaserine			✓			
U016	Benz[c]acridine		✓		✓	✓	
U017	Benzal chloride		✓		✓	✓	
U018	Benz[a]anthracene	✓			✓	✓	✓
U019	Benzene	✓			✓	✓	✓
U020	Benzenesulfonyl chloride		✓		✓	✓	
U021	Benzidine		✓			✓	✓
U022	Benzo[a]pyrene	✓				✓	✓
U023	Benzotrichloride		✓		✓	✓	
U024	Bis(2-chloroethoxy)methane		✓		✓	✓	✓
U025	Bis(2-chloroethyl) ether		✓		✓	✓	✓
U026	N,N-Bis(2-chloroethyl)-2-naphthylamine	✓				✓	✓
U027	Bis(2-chloroisopropyl) ether		✓		✓	✓	✓
U029	Bromomethane		✓			✓	✓
U030	4-Bromophenyl phenyl ether		✓		✓	✓	✓
U031	n-Butyl alcohol	✓			✓	✓	✓
U032	Calcium chromate			✓			
U033	Carbonyl fluoride		✓			✓	✓
U034	Chloral		✓		✓	✓	✓
U035	Chlorambucil		✓			✓	✓
U036	Chlordane		✓		✓	✓	
U037	Chlorobenzene	✓			✓	✓	
U038	Chlorobenzilate	✓			✓	✓	
U039	p-Chloro-m-cresol	✓				✓	
U040	Chlorodibromomethane		✓			✓	✓
U041	1-Chloro-2,3-epoxypropane		✓		✓	✓	✓
U042	Chloroethyl vinyl ether		✓		✓	✓	✓
U043	Chloroethene		✓			✓	✓
U044	Chloroform		✓		✓	✓	✓
U045	Chloromethane		✓			✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U046	Chloromethyl methyl ether		√		√	√	√
U047	2-Chloronaphthalene	√				√	√
U048	2-Chlorophenol	√			√	√	
U049	4-Chloro-o-toluidine hydrochloride		√		√	√	√
U050	Chrysene	√				√	√
U051	Cresote	√			√	√	√
U052	Cresols	√				√	√
U053	Crotonaldehyde	√			√	√	√
U054	Cresylic acid	√			√	√	√
U055	Cumene	√			√	√	√
U056	Cyclohexane	√			√	√	√
U057	Cyclohexanone	√			√	√	√
U058	Cyclophosphamide		√			√	√
U059	Daunomycin		√			√	√
U060	DDD		√			√	
U061	DDT		√			√	
U062	Diallate		√			√	√
U063	Dibenz[a,h]anthracene	√				√	√
U064	Dibenzo[a,i]pyrene	√				√	√
U065	Dibromochloromethane		√		√	√	√
U066	1,2-Dibromo-3-chloropropane		√		√	√	√
U067	1,2-Dibromoethane		√			√	√
U068	Dibromomethane		√			√	√
U069	Di-n-butyl phthalate	√			√	√	√
U070	1,2-Dichlorobenzene		√		√	√	
U071	1,3-Dichlorobenzene		√		√	√	
U072	1,4-Dichlorobenzene		√			√	
U073	3,3'-Dichlorobenzidine		√			√	
U074	1,4-Dichloro-2-butene		√		√	√	√
U075	Dichlorodifluoromethane		√			√	√
U076	1,1-Dichloroethane		√		√	√	√
U077	1,2-Dichloroethane		√		√	√	√
U078	1,1-Dichloroethylene		√		√	√	√
U079	1,2-trans-dichloroethylene		√		√	√	√
U080	Dichloromethane		√		√	√	√
U081	2,4-Dichlorophenol		√			√	
U082	2,6-Dichlorophenol		√			√	
U083	1,2-Dichloropropane		√		√	√	√
U084	1,3-Dichloropropane		√		√	√	√
U085	Diepoxybutane	√			√	√	√
U086	1,2-Diethylhydrazine	√				√	√
U087	O,O-DiethylS-methyl ester of phosphorodithioic acid		√		√	√	√
U088	Diethyl phthalate	√			√	√	√

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration: Good	Candidate for incineration: Potential	Candidate for incineration: Poor	Incinerator type: Liquid injection	Incinerator type: Rotary kiln	Incinerator type: Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U089	Diethylstilbestrol	✓				✓	✓
U090	Dihydrosafrole	✓				✓	✓
U091	3,3'-Dimethoxybenzidine	✓			✓	✓	✓
U092	Dimethylamine	✓				✓	✓
U093	p-Dimethylaminoazobenzene		✓			✓	✓
U094	7,12-Dimethylbenz[a]anthracene	✓				✓	✓
U095	3,3'-Dimethylbenzidine	✓				✓	✓
U096	alpha-alpha-Dimethylbenzylhydroperoxide	✓			✓	✓	✓
U097	Dimethylcarbamoyl chloride		✓			✓	✓
U098	1,1-Dimethylhydrazine		✓		✓	✓	✓
U099	1,2-Dimethylhydrazine		✓		✓	✓	✓
U100	Dimethylnitrosoamine		✓		✓	✓	✓
U101	2,4-Dimethylphenol	✓				✓	✓
U102	Dimethyl phthalate	✓			✓	✓	✓
U103	Dimethyl sulfate		✓		✓	✓	✓
U104	2,4-Dinitrophenol		✓			✓	✓
U105	2,4-Dinitrotoluene		✓			✓	✓
U106	2,6-Dinitrotoluene		✓			✓	✓
U107	Di-n-octyl phthalate	✓			✓	✓	✓
U108	1,4-Dioxane	✓			✓	✓	✓
U109	1,2-Diphenylhydrazine		✓			✓	✓
U110	Dipropylamine		✓		✓	✓	✓
U111	Di-n-propylnitrosamine		✓			✓	✓
U112	Ethyl acetate	✓			✓	✓	✓
U113	Ethyl acrylate	✓			✓	✓	✓
U114	Ethylenebisdithiocarbamate		✓		✓	✓	✓
U115	Ethylene oxide	✓				✓	✓
U116	Ethylene thiourea		✓			✓	✓
U117	Ethyl ether	✓			✓	✓	✓
U118	Ethylmethacrylate	✓				✓	✓
U119	Ethyl methanesulfonate		✓		✓	✓	✓
U120	Fluoranthene	✓				✓	✓
U121	Fluorotrichloromethane		✓			✓	✓
U122	Formaldehyde	✓				✓	✓
U123	Formic acid	✓			✓	✓	✓
U124	Furan	✓			✓	✓	✓
U125	Furfural	✓			✓	✓	✓
U126	Glycidylaldehyde	✓			✓	✓	✓
U127	Hexachlorobenzene		✓			✓	
U128	Hexachlorobutadiene		✓		✓	✓	✓
U129	Hexachlorocyclohexane		✓			✓	✓
U130	Hexachlorocyclopentadiene		✓		✓	✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U131	Hexachloroethane		✓			✓	✓
U132	Hexachlorophene		✓			✓	✓
U133	Hydrazine		✓		✓	✓	✓
U134	Hydrofluoric acid			✓			
U135	Hydrogen sulfide		✓			✓	✓
U136	Hydroxydimethyl arsine oxide			✓			
U137	Indeno(1,2,3-cd)pyrene	✓				✓	✓
U138	Iodomethane		✓		✓	✓	✓
U139	Iron Dextran			✓			
U140	Isobutyl alcohol	✓			✓	✓	✓
U141	Isosafrole	✓			✓	✓	✓
U142	Kepone	✓				✓	✓
U143	Lasiocarpine		✓			✓	✓
U144	Lead acetate			✓			
U145	Lead phosphate			✓			
U146	Lead subacetate			✓			
U147	Maleic anhydride	✓				✓	✓
U148	Maleic hydrazide		✓			✓	✓
U149	Malononitrile		✓			✓	✓
U150	Melphalan		✓			✓	✓
U151	Mercury			✓			
U152	Methacrylonitrile		✓		✓	✓	✓
U153	Methanethiol		✓			✓	✓
U154	Methanol	✓			✓	✓	✓
U155	Methapyrilene		✓		✓	✓	✓
U156	Methyl chlorocarbonate		✓		✓	✓	✓
U157	3-Methylcholanthrene	✓				✓	✓
U158	4,4'-Methylene-bis-(2-chloroaniline)	✓				✓	✓
U159	Methyl ethyl ketone	✓			✓	✓	✓
U160	Methyl ethyl ketone peroxide	✓			✓	✓	✓
U161	Methyl isobutyl ketone	✓			✓	✓	✓
U162	Methyl methacrylate	✓			✓	✓	✓
U163	N-Methyl-N'-nitro-N-nitrosoguanidine		✓		✓	✓	✓
U164	Methylthiouracil		✓			✓	✓
U165	Naphthalene	✓				✓	✓
U166	1,4-Naphthoquinone	✓				✓	✓
U167	1-Naphthylamine		✓			✓	✓
U168	2-Naphthylamine		✓			✓	✓
U169	Nitrobenzene		✓		✓	✓	✓
U170	4-Nitrophenol		✓			✓	✓
U171	2-Nitropropane		✓			✓	✓
U172	N-Nitrosodi-n-butylamine		✓		✓	✓	✓
U173	N-Nitrosodiethanolamine		✓		✓	✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U174	N-Nitrosodiethylamine		✓		✓	✓	✓
U175	N-Nitrosodi-n-propylamine		✓		✓	✓	✓
U176	N-Nitroso-n-ethylurea		✓			✓	✓
U177	N-Nitroso-n-methylurea		✓			✓	✓
U178	N-Nitroso-n-methylurethane		✓			✓	✓
U179	N-Nitrosopiperidine		✓		✓	✓	✓
U180	N-Nitrosopyrrolidine		✓		✓	✓	✓
U181	5-Nitro-o-toluidine		✓			✓	✓
U182	Paraldehyde	✓			✓	✓	✓
U183	Pentachlorobenzene		✓			✓	
U184	Pentachloroethane		✓		✓	✓	✓
U185	Pentachloronitrobenzene		✓			✓	✓
U186	1,3-Pentadiene	✓				✓	✓
U187	Phenacetin		✓			✓	✓
U188	Phenol	✓	✓			✓	✓
U189	Phosphorous sulfide		✓			✓	✓
U190	Phthalic anhydride	✓				✓	✓
U191	2-Picoline		✓		✓	✓	✓
U192	Pronamide		✓			✓	✓
U193	1,3-Propane sultone		✓			✓	✓
U194	n-Propylamine		✓			✓	✓
U196	Pyridine		✓		✓	✓	✓
U197	Quinones	✓				✓	✓
U200	Reserpine		✓			✓	✓
U201	Resorcinol	✓				✓	✓
U202	Saccharin		✓			✓	✓
U203	Safrole	✓			✓	✓	✓
U204	Selenious acid			✓			
U205	Selenium sulfide			✓			
U206	Streptozotocin		✓			✓	✓
U207	1,2,4,5-Tetrachlorobenzene		✓		✓	✓	✓
U208	1,1,1,2-Tetrachloroethane		✓		✓	✓	✓
U209	1,1,2,2-Tetrachloroethane		✓		✓	✓	✓
U210	Tetrachloroethane		✓		✓	✓	✓
U211	Tetrachloromethane		✓			✓	✓
U212	2,3,4,6-Tetrachlorophenol		✓			✓	✓
U213	Tetrahydrofuran	✓			✓	✓	✓
U214	Thallium acetate			✓			
U215	Thallium carbonate			✓			
U216	Thallium chloride			✓			
U217	Thallium nitrate			✓			
U218	Thioacetamide		✓			✓	✓
U219	Thiourea		✓			✓	✓

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Discarded commercial chemical products, off-specification species, containers, and spill residues thereof (cont'd)							
U220	Toluene	√			√	√	√
U221	Toluenediamine		√			√	√
U222	o-Toluidine hydrochloride		√		√	√	√
U223	Toluene diisocyanate		√		√	√	√
U224	Toxaphene		√			√	√
U225	Tribromomethane		√		√	√	√
U226	1,1,1-Trichloroethane		√		√	√	√
U227	1,1,2-Trichloroethane		√		√	√	√
U228	Trichloroethane		√		√	√	√
U229	Trichlorofluoromethane		√		√	√	√
U230	2,4,5-Trichlorophenol		√			√	
U231	2,4,6-Trichlorophenol		√			√	
U232	2,4,5-Trichlorophenoxyacetic acid		√			√	
U233	2,4,5-Trichlorophenoxypropionic acid alpha, alpha, alpha-Trichlorotoluene		√			√	
U234	Trinitrobenzene		√			√	√
U235	Tris(2,3-dibromopropyl) phosphate		√			√	√
U236	Trypan blue		√			√	√
U237	Uracil mustard		√			√	√
U238	Urethane	√				√	√
U239	Xylene	√			√	√	√
Other hazardous wastes							
SIC code number							
2865	Vacuum still bottoms from the production of maleic anhydride	√				√	√
2865	Distillation residues from fractionating tower for recovery of benzene and chlorobenzenes		√			√	
2865	Vacuum distillation residues from purification of 1-chloro-4-nitrobenzene		√			√	√
2865	Still bottoms or heavy ends from methanol recovery in methyl methacrylate production	√				√	√
2869	Heavy ends and distillation from production of carbaryl	√				√	√
2869	Residues from the production of hexachlorophenol, trichlorophenol and 2,4,5-T		√			√	√
2869	Heavy ends from distillation of ethylene dichloride in vinyl chloride production		√			√	√
2869	Solid waste discharge from ion exchange column in production of acrylonitrile		√			√	√
2869	Bottom stream from quench column in acrylonitrile production of acrylonitrile	√			√	√	√
2869	Still bottoms from aniline production	√				√	√
2869	Tars from manufacture of bicycloheptadiene and cyclopentadiene	√				√	√
2869	Still bottom from production of furfural	√				√	√
2869	Unrecovered triester from production of disulfoton		√			√	√
2295	Waste polyvinyl chloride (PVC) from the manufacture of coated fabrics		√			√	√
2869	Still bottoms from the production of pentachloronitrobenzene		√			√	

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Other hazardous wastes (cont'd)							
SIC code number							
2869	Process clean out sludges from production of 1,1,1-trichloroethane		√			√	√
2869	Heavy ends and light ends from the production of methyl acrylate	√				√	√
2822	Polyvinyl chloride sludge from the manufacture of polyvinyl chloride		√			√	√
2869	Still bottoms from the purification of fluoromethanes in the production of fluoromethanes		√			√	√
2869	Heavy ends and light ends from the production of ethyl acrylate	√				√	√
2869	Heavy ends from the production of glycerine from allyl chloride	√				√	√
2869	Heavy ends from the distillation of acetic anhydride in the production of acetic anhydride	√				√	√
2869	Light ends from the distillation of acetaldehyde in the production of acetic anhydride	√			√	√	√
	· Reactor cleanup wastes from the chlorination, dehydrochlorination or oxychlorination of aliphatic hydrocarbons		√		√	√	√
	· Fractionation bottoms from the separation of chlorinated aliphatic hydrocarbons		√		√	√	√
	· Distillation bottoms from the separation of chlorinated aliphatic hydrocarbons		√		√	√	√
	· Reactor cleanup wastes from the chlorination or oxychlorination of cyclic aliphatic hydrocarbons		√		√	√	√
	· Fractionation bottoms from the separation of chlorinated cyclic aliphatic hydrocarbons		√		√	√	√
	· Distillation bottoms from the separation of chlorinated cyclic aliphatic hydrocarbons		√		√	√	√
	· Batch residues from the batch production of chlorinated polymers		√			√	√
	· Solution residues from the production of chlorinated polymers		√		√	√	√
	· Reactor cleanup wastes from the chlorination of aromatic hydrocarbon		√		√	√	
	· Fractionation bottoms from the separation of chlorinated aromatic hydrocarbons		√		√	√	
	· Distillation bottoms from the separation of chlorinated aromatic hydrocarbons		√		√	√	
3333	Zinc production: oxide furnace residue and acid plant sludge			√			
3339	Ferromanganese emissions control: baghouse dusts and scrubwater solids			√			
3339	Ferrochrome silicon furnace emission control dust or sludge			√			
3339	Ferrochrome emissions control: furnace baghouse dust, and ESP			√			
3339	Primary antimony-pyrometallurgical blast furnace slag			√			
3341	Secondary lead, scrubber sludge from SO_2 emission control, soft lead production			√			

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Other hazardous wastes (cont'd)							
SIC code number							
3341	Secondary lead-white metal production furnace dust			√			
3341	Secondary copper-pyrometallurgical, blast furnace slag			√			
3341	Secondary copper-electrolytic refining wastewater treatment sludge			√			
3341	Secondary aluminum dross smelting-high salt slag plant residue			√			
3341	Zinc-cadmium metal reclamation, cadmium plant residue			√			
3691	Lead acid storage battery production wastewater treatment sludges			√			
3691	Lead acid storage battery production cleanup wastes from cathode and anode paste production			√			
3691	Nickel cadmium battery production wastewater treatment sludges			√			
3691	Cadmium silver oxide battery production wastewater treatment sludges			√			
3691	Mercury cadmium battery production wastewater treatment sludges			√			
3692	Magnesium carbon battery production chromic acid wastewater treatment sludges			√			
2816	Ash from incinerated still bottoms (paint and pigment production)			√			
2819	Arsenic bearing wastewater treatment sludges from production of boric acid			√			
2834	Arsenic or organo-arsenic containing wastewater treatment sludges from production of veterinary pharmaceuticals			√			
2851	Wastewater treatment sludges from paint production			√			
2851	Air pollution control sludges from paint production			√			
2869	By-product salts in production of MSMA			√			
2869	By-product salts in production of cacodylic acid			√			
2869	Lead slag from lead alkyl production			√			
3312	Steel Finishing: Alkaline cleaning waste · Waste pickle liquor · Cyanide-bearing wastes from electrolytic coating · Chromate and dichromate wastes from chemical treatment · Descaling acid			√			
3322	Lead/phenolic sand-casting waste from malleable iron foundries			√			
3331	Primary copper smelting and refining electric furnace slag, converter dust, acid plant sludge, and reverberatory dust (T)			√			
3332	Primary lead blast furnace dust			√			
3339	Primary antimony-electrolytic sludge			√			
3339	Primary tungsten-digestion residue			√			
1094	Waste rock and overburden from uranium mining			√			
1099	Chlorinator residues and clarifier sludge from zirconium extraction			√			
1475	Overburden and slimes from phosphate surface mining			√			
2874	Waste gypsum from phosphoric acid production			√			
2819-2874	Slag and fluid bed prills from elemental phosphorus production			√			
2812	Sodium calcium sludge from production of chlorine by Down Cell process			√			
2812	Mercury bearing brine purification muds from mercury cell process in chlorine production			√			

(continued)

TABLE 3-1 (continued)

EPA hazardous waste number	Hazardous waste	Candidate for incineration			Incinerator type		
		Good	Potential	Poor	Liquid injection	Rotary kiln	Fluidized bed
Other hazardous wastes (cont'd)							
SIC code number							
2816	Mercury bearing wastewater treatment sludges from the production of mercuric sulfide pigment			√			
2816	Chromium bearing wastewater treatment sludges from the production of TiO_2 pigment by the chloride process			√			
2816	Arsenic bearing sludges from purification process in the production of antimony oxide			√			
2816	Antimony bearing wastewater treatment sludge from production of antimony oxide			√			
3312	Iron making: Ferromaganese blast furnace dust · Ferromanganese blast burnace sludge · Electric furnace dust and sludge			√			

---

[a] Use this table for indicative guidance only. For decision making, read the material presented in the text.

- Moisture content
- Potential pollutants present in incinerator effluents
- Inert content
- Heating value and auxiliary fuel requirements
- Potential health and environmental effects
- Physical form
- Corrosiveness
- Quality
- Known carcinogenic content
- PCB content.

Table 3-1 should be used with caution. The information is indicative rather than conclusive. Conclusive decisions can be made only after studying the actual physical, chemical, and thermodynamic characteristics of the material(s) along with trial burn data (if available), and comparing expected behavior with the known behavior of a similar material (similar composition or physical, chemical, and thermodynamic characteristics) undergoing thermal destruction.

The incineration technology ratings in Table 3-1 are influenced by the physical form of the waste. In general, liquid wastes can be incinerated by a liquid injection incinerator, rotary kiln, or fluidized bed incinerator. Waste in gas, liquid, solid, and mixture forms can be incinerated by either a rotary or fluidized bed incinerator. The kinematic viscosity of the liquid waste has to be considered in determining its suitability for incineration by liquid injection incinerators.

Liquid injection, and rotary kiln incinerators are widely used to dispose of hazardous wastes. There is substantial research going on fluidized bed incinerators and they appear to be promising in disposing of hazardous wastes. Multiple hearths and multiple chambers incinerators have moderate applicability for incineration of hazardous wastes. They are widely used for the destruction of solids (municipal refuse) and sludges (sewage sludges). If the ash resulting from incineration of a waste is fusible, multiple hearths incinerators are not well suited for its disposal. Multiple hearth incinerators are not capable of operating at elevated temperatures - so that if a temperature over 2000°F is needed for destruction, multiple hearths incinerators are not applicable. Multiple hearths and multiple chambers incinerators have limited applicability to hazardous wastes, so they are not included in Table 3-1.

It may be possible to blend different wastes or wastes and fuel oils to change poor or potential candidates into good candidates for incineration. Such blending may also change the characteristics of a waste, making it incinerable in a different incineration type than is identified in Table 3-1. It is also possible that some wastes identified in Table 3-1 as good or potential candidates may turn out to be poor candidates for incineration if mixed with or contaminated by poor incineration candidates like metals (arsenic, chromium, etc.). Therefore, such factors as blending and waste contamination should be considered on a case-by-case basis in making decisions. As mentioned earlier, Table 3-1 should be used with caution for indicative guidance rather than conclusive decisions.

3.3 WASTE SAMPLING [9]

It is important that a representative sample of the waste be collected and properly handled in determining waste characteristics. Sampling situations vary widely and therefore no universal sampling procedure can be recommended. However, it is important to incorporate quality assurance procedures as necessary components in any waste sampling plan.

Sampling procedures require a plan of action to maximize safety of sampling personnel, minimize sampling time and cost, reduce errors in sampling, and protect the integrity of the samples after sampling. The following steps are essential in this plan of action:

1. Prior to collecting a sample, check the manifest to see whether dangerous emissions can be expected and to make sure that what is sampled resembles what is described in the manifest.
2. Ask the generator for background information on the waste.
3. Determine what should be sampled (truck, barrel, pond, etc.).
4. Select the proper sampler (Coliwasa, scoop, bucket, etc.).
5. Select the proper sample container and closure (glass, plastic, etc.).
6. Design an adequate sampling plan that includes the following:

   (a) Choice of the proper sampling point. (b) Determination of the number of samples to be taken. (c) Determination of the volumes of samples to be taken.
7. Observe proper sampling precautions (safety of personnel, protective gear).
8. Handle samples properly (sample preservation).
9. Identify samples and protect them from tampering.
10. Record all sample information in a field notebook.
11. Fill out chain of custody record.
12. Fill out sample analysis request sheet.
13. Deliver or ship the samples to the laboratory for analysis.

Various samplers and their applicabilities; sample containers and their compatibility with wastes; sampling points, number of samples and sample volume requirements; personnel protective gear and other safety precautions; sample preservation requirements; sampling procedures for various situations; and sample handling (labeling, field logging, chain of custody, analysis request form and sample shipping) are discussed in detail in "Samplers and Sampling

Procedures for Hazardous Waste Streams" (EPA-600/2-80-018, January 1980). This source can be consulted prior to sampling.

Chain of custody procedures recommended by EPA's National Field Investigation Center are described below:

1. The laboratory director designates one full-time employee (usually the laboratory supervisor) as a sample custodian and one other person as an alternate. In addition, the laboratory sets aside a "sample storage security area." This is a clean, dry, isolated room which can be securely locked.

2. All samples are handled by the minimum number of persons.

3. All incoming samples are received only by the custodian or, in his absence, the alternate, who indicates receipt by signing the sample transmittal sheets and, as appropriate, sample tags, accompanying the samples and retaining the sheets as permanent records.

4. Immediately upon receipt, the custodian places the sample in the sample room, which is locked at all times except when the samples are removed or replaced by the custodian. To the maximum extent possible, only the custodian is permitted in the sample room.

5. The custodian ensures that heat-sensitive or light-sensitive samples, or other sample materials having unusual physical characteristics, or requiring special handling, are properly stored and maintained.

6. Only the custodian, or in his absence, the alternate, distributes samples to, or divides them among, personnel performing tests. The custodian enters into a permanent log book the laboratory sample number, time and date, and the name of the person receiving the sample. The receiver also signs the entry.

7. Laboratory personnel are then responsible for the care and custody of the sample until analytical tests are completed. Upon completion of tests unused portion of the sample together with all identifying tags and laboratory records are returned to the custodian, who records the appropriate entries in the log book. These, and other records are retained as appropriate.

8. The analyst records in his laboratory notebook or worksheet the name of the person from whom the sample was received, whether it was sealed, identifying information describing the sample (by origin and sample identification number), the procedures performed, and the results of the testing. If deviations from approved analytical procedures occur, the analyst is prepared to justify this decision under cross-examination. The notes are signed and dated by the person performing the tests. If that person is not available as a witness at time of trial the government may be able to introduce the notes in evidence under the Federal Business Records Act.

Samples, tags, and laboratory records of tests may be destroyed only upon the written order of the laboratory director, who ensures that this information is no longer required.

The Field Sampling Chain of Custody Form should be completed by the field sampling team and included with the shipping container when sent to the contractor's laboratory. A separate form should be included with each box of samples, listing the samples contained in that box. A sample of a completed form is included for reference (Figure 3-1).

A copy of chain of custody procedures can be obtained by contacting:

National Field Investigation Center
U.S. Environmental Protection Agency
Denver Federal Center
Building #53, Box 25227
Denver, Colorado 80225
Telephone: (303) 234-4650

Other reference materials that can be consulted before developing a sampling plan are listed below.

1. Sampling petroleum and petroleum products; Method ASTM D270.
2. Sampling industrial chemicals; Method ASTM E300.
3. Benedetti-Pichler, A. A. Theory and principles of sampling for chemical analysis. In: Walfer, E. J.; and Bell, G., eds. Physical methods in chemical analysis, Vol. 3. New York, Academic Press, Inc., 1956.
4. Preparing coal samples for analysis; Method ASTM D2013.
5. Sampling coke for analysis; Method ASTM D345.
6. Guidelines establishing test procedures for the analysis of pollutants, proposed regulations. Federal Register. 44(233):69464-69575, 1979 December 3.
7. Procedures for level 2 sampling and analysis of organic materials. Research Triangle Park, NC; U.S. Environmental Protection Agency; 1979 February. 164 p. EPA-600/7-79-033.
8. Test Methods for Evaluating Solid Waste - Physical/Chemical Methods; SW-646-1980.
9. Hazardous Waste and Consolidated Permit Regulations, Federal Register. 45(98):33063-33285. 1980 May 19.

3.4 BASIC ANALYSIS OF WASTE [10, 12]

This section discusses the basic physical and chemical information about a waste that may be required in determining its feasibility for incineration and

FIELD SAMPLING CHAIN OF CUSTODY FORM

LEADER	NAME OF SURVEY OR ACTIVITY	DATE OF COLLECTION	SHEET
Melvin	Priority Pollutant Survey 523.10	9/12/84	1 of 1

DESCRIPTION OF SHIPMENT

TYPE OF SAMPLE Water Samples

TOTAL NUMBER SAMPLE CONTAINERS 10

CONTENTS OF SHIPMENT

FIELD	NO. OF CONTAINERS/FIELD NO.			ANALYSES REQUIRED - CHECK WHERE APPROPRIATE						
SAMPLE NO.	PLASTIC	GLASS	VOA	CYANIDE	PHENOLS	ASBESTOS	PESTICIDES	METALS	VOA	SEMI-
0876	1			✓						
0895		2					✓			
1992	1							✓		
3862	1					✓				
3812			3						✓	
6413		1			✓					
6863		1								

PERSONNEL CUSTODY RECORD

RELINQUISHED BY (SAMPLER)	RECEIVED BY	DATE	TIME	REASON
H. Melvin	Harpy Airlines	10/1/84	1600	Delivery to lab
SEALED UNSEALED	X SEALED UNSEALED			
RELINQUISHED BY	RECEIVED BY	DATE	TIME	REASON
Airline	Vendor	10/3/84	900	

Figure 3-1. Field sampling chain of custody form.

its compatibility for a given incineration facility and in designing an incineration facility. Basic hazardous waste data helpful in selecting an incineration system are as follows:

- Type(s) of waste: Physical form - liquid, gas, solid, or mixture
- Ultimate analysis: C, H, O, N, S, P, Cl, F, Br, I, ash, moisture
- Heating value: Btu/lb
- Solids: Size, form, and quantity
- Liquids: Viscosity as a function of temperature, specific gravity
- Sludges: Density, viscosity, and percent solids
- Slurries: Density, viscosity, and percent solids
- Gases: Density
- Special characteristics: Toxicity, corrosiveness, and other unusual features
- Disposal rate: Peak, average, and minimum (present and future)
- Trace metals: As, Ba, Cd, Cr, Pb, Hg, Se, Ag
- Major organic compound groups: e.g., aromatics, aliphatics, etc.

It may not be necessary to follow the complete, elaborate analysis protocol for each shipment of waste from the same source, unless the material is entirely different from earlier shipments. How often the shipments should be sampled, and for what parameters samples should be analyzed, should be determined on a case-by-case basis using best engineering judgment by the user of this handbook.

In matching different wastes with commercial incineration facilities, the physical form (solid, liquid, etc.) of the wastes is very important. The criteria used for matching different wastes to the various incineration facilities are:

(1) Physical form:

Gas, liquid, slurry, sludge, or solid

(2) Temperature range required for destruction:

(a) >2,000°F (>1,087°C)
(b) 1,400-2,000°F (757-1,087°C)
(c) 700-1,400°F (367-757°C)
(d) <700°F (<367°C)

(3) Off-gases:

  (a) Essentially oxides of carbon and nitrogen, and water vapor
  (b) Halogen, sulfur, phosphorus or volatile metal species

(4) Ash:

  Nonfusible, fusible, or metallic

(5) Heating value:

  (a) 10,000 Btu/lb (>23 MJ/kg)
  (b) 5,000-10,000 Btu/lb (12-23 MJ/kg)
  (c) 5,000 Btu/lb (<12 MJ/kg)

Liquid injection, fluidized bed, and rotary kiln incinerators are widely used to dispose of hazardous waste. A particular incinerator may be better suited for incineration of a particular type of waste based on the physical characteristics of the waste. Solids, sludges, and slurries of high viscosity liquids can be disposed in rotary kiln or fluidized bed incinerators, but not in a liquid injection incinerator. If the ash resulting from the incineration of a waste is fusible, fluidized bed incinerators are not well suited for its disposal. Furthermore, fluidized bed incinerators are not capable of operating at elevated temperatures, so if a temperature over 2,000°F (1,087°C) is needed for destruction, rotary kilns or liquid injection incinerators are applicable. Fluidized bed incinerators are generally not operated at temperatures above 1,500°F.

The percentages of carbon, hydrogen, oxygen, nitrogen, sulfur, halogens, and phosphorus in the waste, as well as its moisture content, need to be known to calculate stoichiometric combustion air requirements and to predict combustion gas flow and composition. The presence of halogenated and sulfur-bearing waste can result in the formation of HCl, HF, H_2S, and SO_2 in the incinerator gases. These must be removed with suitable scrubbing equipment before discharge to the atmosphere. Also, in the incineration of organic wastes containing chlorine, sufficient hydrogen should be provided by either the waste or auxiliary fuel for the chlorine to form HCl and not Cl_2. Nitrogen oxides are produced during high temperature combustion by reaction between nitrogen and oxygen in the air. Their formation can be reduced by reducing combustion temperature or excess air, but such controls may cause the formation of other pollutants. Nitrogen content of waste material is generally low, but the presence of nitrogen-containing materials (nitrates, ammonium compounds, etc.) can greatly increase the NO_x emissions.

Trace metals (arsenic, barium, cadmium, chromium, mercury, lead, selenium, and silver) are a potential cause for concern in incinerator emissions. Analyses for them should be performed unless it is known that they are or are not present in the waste. Wastes containing significant amounts of metals will generally be poor candidates for incineration. Such wastes will require postcombustion emission control of a special type, and the effluent or solid waste from the emission control device must in turn be treated as a hazardous waste, although considerably reduced in volume and weight from the original hazardous waste.

Ash content of the waste should be determined to evaluate the potential for excessive slag formation as well as potential particulate emissions from the incinerators. Kinematic viscosity and the size and concentration of solids in a liquid waste are the most important physical properties to consider in evaluating a liquid waste incinerator design. The physical handling system and burner atomization techniques are dependent on viscosity and solid content of the waste. Chemically complex sludges may contain such elements as Na, K, Mg, P, S, Fe, Al, Ca, Si, O_2, N_2, C and H_2. Several chemical reactions can be expected to take place in the high temperature oxidizing atmosphere of an incineration operation of chemically complex sludges. Resulting ash may contain Na_2SO_4, Na_2CO_3, NaCl, etc. Pure Na_2SO_4 has a melting point of 1,623°F. Pure Na_2CO_3 has a melting point of 1,564°F. However, mixtures of these two compounds have melting points lower than either one of the two by themselves. At 47% Na_2SO_4 - 53% Na_2CO_3, the melting point is 1,552°F. Sodium chloride has a melting point of 1,472°F. In combination with Na_2CO_3, sodium chloride will lower the melting point of the mixture. At 62 mole % Na_2CO_3, the eutectic melting point is 1,172°F. Likewise, mixtures of NaCl and Na_2SO_4 form low melting mixture with the eutectic melting point of 1,154°F for a 65 mole % Na_2SO_4 mixture. When all three of these compounds are present, a mixture melting point as low as 1,134°F is possible. So sludges containing substantial amounts of sodium can cause defluidization of fluidized bed by forming low melting eutectic mixtures. Furthermore, if the particles of the fluidized bed are silica-sand, Na_2SO_4 will react with the silica to form a viscous sodium-silicate glass, which will cause rapid defluidization.

The heating value of a waste corresponds to the quantity of heat released when the waste is burned, commonly expressed as Btu/lb. It should be considered in establishing an energy balance for the combustion chamber and in assessing the need for auxiliary fuel firing. As a rule of thumb, a minimum heating value of about 8,000 Btu/lb is required to sustain combustion.

Special characteristics of the waste such as extreme toxicity, mutagenicity or carcinogenicity, corrosiveness, fuming, odor, pyrophoric properties, thermal instability, shock sensitivity, and chemical instability should also be considered in incinerator facility design. Thermal or shock instability are of particular concern from a combustion standpoint, since wastes with these properties pose an explosion hazard. Other special properties relate more directly to the selection of waste handling procedures and air pollution control requirements.

Chapter 4 discusses detailed procedures for evaluating the design and compatibility of incinerators with the basic physical, chemical, and thermodynamic properties of the waste.

3.5 SUPPLEMENTAL ANALYSIS OF WASTE

In addition to its basic analysis, supplemental analysis of waste to identify and quantify its major chemical components will be helpful in evaluating waste for incineration. This information will help to determine whether or not the waste is similar to others that have been successfully incinerated previously, in a similar facility or in the existing facility. The necessary supplemental information may be available from sources described in Section 3.2. For example, the waste generator may have previously analyzed the waste stream or may have a sufficiently thorough understanding of the process generating the waste to adequately characterize it.

The supplemental analyses that may be necessary to determine whether a waste can be effectively incinerated and/or whether a trial burn is required are the following:

- Level 1 organic analysis
- Specific organic analysis
- Trace metal scan
- Thermal decomposition unit analysis

3.6 ANALYSIS TEST METHODS

All the physical, chemical, and thermodynamic analyses of the waste should be conducted following ASTM, EPA, or EPA-sponsored equivalent methods. The May 19, 1980 Federal Register (pages 33130 and 33131) identifies approved measurement techniques for each organic chemical and inorganic species (heavy metals) listed in Section 3001 of RCRA (May 19, 1980 Federal Register). Additional reference materials that can be consulted for analytical guidance are listed below:

1. ASTM books.

2. Test methods for evaluating solid waste. Washington, DC; U.S. Environmental Protection Agency; 1980 May. EPA SW-846.

3. Lentzen, D. E.; Wagoner, D. E.; Estes, E. D.; and Gutknecht, W. F. IERL-RTP procedures manual: level 1 environmental assessment, second edition. Research Triangle Park, NC; U.S. Environmental Protection Agency; 1978 October. 279 p. EPA 600/7-78-201.

4. Guidelines establishing test procedures for the analysis of pollutants, proposed regulations. Federal Register. 44(233):69464-69575, 1979 December 3.

5. Procedures for level 2 sampling and analysis of organic materials. Research Triangle Park, NC; U.S. Environmental Protection Agency; 1979 February. 164 p. EPA-600/7-79-033.

6. Standard methods for the examination of water and wastewater, 14th ed. Washington, American Public Health Association, 1976. 1193 p.

7. Methods for chemical analysis of water and wastes. Cincinnati, OH; U.S. Environmental Protection Agency; 1979 March. 463 p. EPA-600/4-79-020.

8. Hauser, R.; and Cummins, R. L. Increasing sensitivity of 3-methyl-2-benzothiazolone hydrazone test for analyses of aliphatic aldehydes in air. Analytical Chemistry. 56:679, 1964.

9. Kraak, J. C.; and Huber, J. F. K. Separation of acidic compounds by high-pressure liquid-liquid chromatography involving ion-pair formation. Journal of Chromatography. 102:331-351, 1974.

10. Smythe, L. E. Analytical chemistry of pollutants. In: Bockris, J. O'M., ed. Environmental chemistry. New York, Plenum, 1977.

Thermal decomposition unit analysis is briefly discussed in Section 3.7.

3.7 THERMAL DECOMPOSITION UNIT ANALYSIS [11]

In the interest of safety, it may be necessary that knowledge of the thermal decomposition properites of a toxic organic substance be obtained before large-scale incineration is conducted.

In response to this need, a laboratory system has been designed and assembled by the University of Dayton Research Institute (UDRI) under EPA sponsorship. This thermal decomposition analytical system (TDAS) is a closed, continuous system which consists of a versatile thermal decomposition unit followed by in-line dedicated gas chromatograph-mass spectrometer-data handling computer (GC-MS-COMP). The objective of this laboratory system is to provide fundamental thermal decomposition data on a wide variety of organic materials - gases, liquids, and solids (including polymers).

Thermal decomposition tests were conducted with the TDAS on polychlorinated biphenyls (PCB's) and on "Hex" wastes. The PCB's were found to have high thermal stability in air. Furthermore, in oxygen-deficient atmospheres their thermal stability is increased by at least 390°F (200°C) over that experienced in air. Several chlorinated, aromatic compounds were still present after exposure to 1,470°F (800°C). Further increases in temperature to 1,830°F (1,000°C) decomposed all compounds except for low levels of hexachlorobenzene.

Figures 3-2, and 3-3, illustrate decomposition of hexachlorobiphenyl in air, decomposition of pentachlorobiphenyl in different gaseous atmospheres, respectively. Figure 3-4 shows the relative concentration of hexachlorobenzene in "Hex" wastes after different thermal exposures.

The UDRI thermal decomposition analytical system, decomposition experiments, resulting test data and their interpretation are discussed in detail in Appendix E. Also, the following articles can be consulted for more information on TDAS:

1. Rubey, W. A. Design consideration associated with the development of a thermal decomposition analytical system (TDAS). Dayton, OH; University of Dayton Research Institute; 1979 May. Technical Report UDR-TR-79-34 (EPA Grant No. R805 117-01-0).

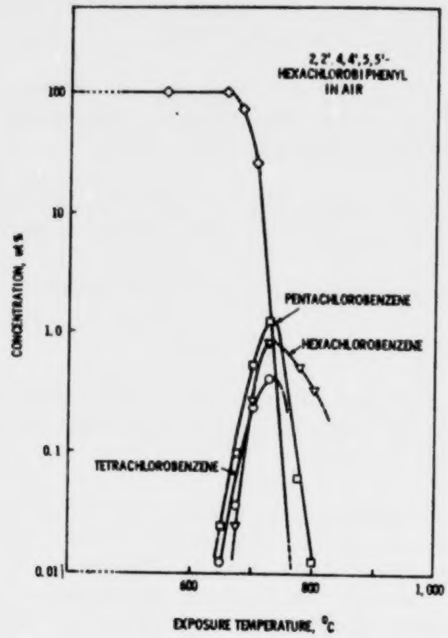


Figure 3-2. Decomposition of hexachlorobiphenyl [11].

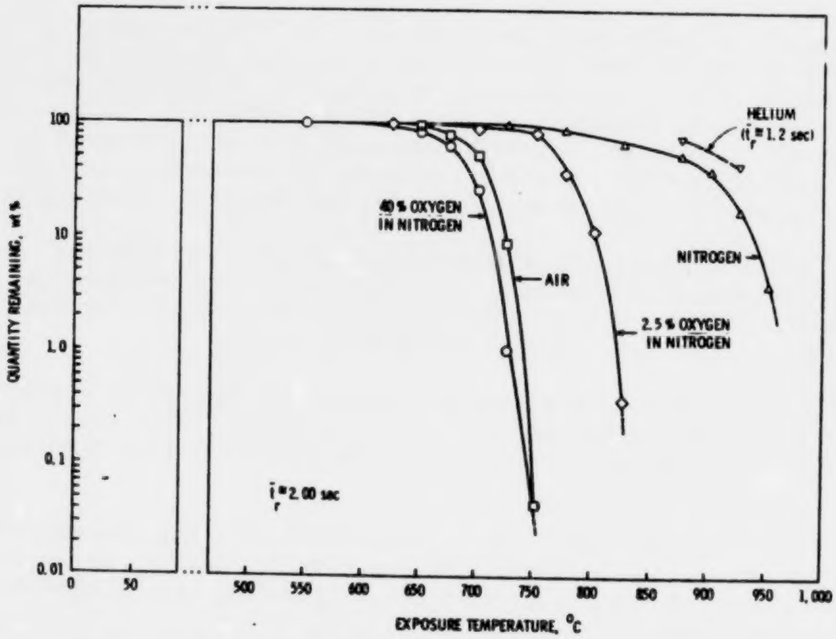


Figure 3-3. Decomposition of pentachlorobiphenyl in different gaseous atmospheres [11].

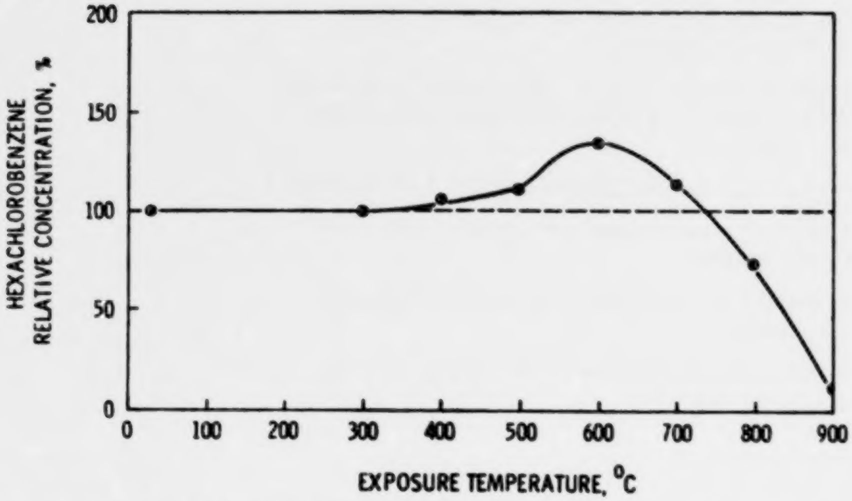


Figure 3-4. Relative concentration of hexachlorobenzene in "Hex" wastes after different thermal exposures.

2. Duvall, D. S.; Rubey, W. A.; and Mescher, J. A. High temperature decomposition of organic hazardous waste. Treatment of hazardous waste, proceedings of the sixth annual research symposium. Cincinnati, OH; U.S. Environmental Protection Agency; 1980 March. p. 121-131. EPA-600/9-80-011.

The temperature, residence time, and oxygen required to destroy a given waste by incineration can be determined by thermal decomposition unit analysis or by a pilot- or full-scale trial burn. It is not necessary to generate temperature, residence time, and oxygen requirement data for wastes for which such data already exist. Trial burn data for some wastes are presented in Appendices F and G.

3.8 WORK SHEET

The work sheet presented in this section is designed to help evaluate a waste for incineration in light of the information presented in this chapter for waste characterization.

WORK SHEET

	Yes	No*
1. Background Information		
· Is background information available and known?	___	___
· Is the SIC code of the waste generating source known?	___	___

	Yes	No*
• Does the waste fall into an EPA hazardous waste classification?		
• If the waste falls into an EPA hazardous waste classification, is the EPA hazardous waste number known?		
• Any special characteristics of the waste known?		
• Are principal waste components and their percentages known?		
• Is the detail of the process generating the waste known?		
• Is the waste hazard class according to DOT regulations known?		

2. Waste Sampling

	Yes	No*
• Is the waste sampled with a compatible sampling device?		
• Is the waste collected in a compatible sample container?		
• Was sampling plan adequate to collect representative samples (determination of sampling points, number of samples, and samples' volumes)?		
• Were the samples properly handled (preservation, labeling, and shipping)?		
• Was pertinent information adequately recorded in the field log book?		
• Were the chain of custody procedures recommended by EPA's National Field Investigation Centers followed?		

3. Basic Analysis Information

	Yes	No*
• Are data for specific basic analysis known?		
- Physical state of waste at 25°C		
- Single phase		
- Multiphase		
- Vapor pressure		
- Viscosity		
- Specific gravity		
- Melting point		
- Boiling point		
- Flash point		
- Solids (size, form, and quantity)		

	Yes	No*
- pH	___	___
- Trace metals (As, Ba, Cd, Cr, Hg, Pb, Se, Ag)	___	___
- Net heating value	___	___
- Elemental analysis (C, H, O, N, S, P, Cl, F, Br, I)	___	___
- Ash content	___	___
- Moisture content	___	___
- PCB's	___	___
- Presence of		
Carcinogen	___	___
Pesticide	___	___
Odor	___	___
- Toxicity	___	___
Ingestion	___	___
Inhalation	___	___
Dermal	___	___
Eyes	___	___
- Reactivity	___	___
- Fire hazard	___	___
- Radioactivity	___	___

4. Supplemental Analysis Information

· Are the major chemical components of the waste and their percentages known?	___	___
· If waste is known or suspected to contain potentially hazardous metals other than those listed in basic analysis information, are their percentages known?	___	___
· Has the waste been tested for thermal decomposition analysis?	___	___
· Are the temperature and residence time necessary for destruction as determined by TDAS known?	___	___
· Are any principal hazardous particle decomposition products identified by TDAS?	___	___
· Has the waste been incinerated before and, if so, in what type of incineration technology?	___	___

5. Other Information

· Are past disposal practices for the waste known?	___	___
· Are any other wastes similar to the one under consideration known for good or potential incineration?	___	___
· Has the proposed facility and/or technology been used before to destroy a similar or like waste?	___	___
· Are waste generation rates (i.e., peak, average, and minimum) known (present and future)?	___	___
· Are there any trial burn data available for the waste?	___	___

	Yes	No*
• Are any potential health and environmental effects of the waste known?	___	___
6. Waste Incineration Decision		
• Can a decision be made about waste incineration with the available information about the waste and information available from this chapter and Chapter 4?	___	___
• If answer is no to the above question, will any additional waste characterization information help to make a decision about waste incineration?	___	___
• If answer is no to the above question, will a trial burn be necessary?	___	___

---

*Any response in the "No" column may indicate the possibility that the information provided is not sufficient for a decision, and additional information may be required.

3.9 REFERENCES

1. Hazardous waste and consolidated permit regulations. Federal Register. 45(98):33121-33133, 1980 May 19.

2. Assessment of industrial hazardous waste practices: leather tanning and finishing industry. Washington, DC; U.S. Environmental Protection Agency; 1976 November. 233 p. EPA SW-131C.

3. Assessment of hazardous waste practices in the petroleum refining industry. Washington, DC; U.S. Environmental Protection Agency; 1976 June. 353 p. EPA SW-129C.

4. Assessment of industrial hazardous waste practices: paint and allied products industry, contract solvent reclaiming operations, and factory application of coatings. U.S. Environmental Protection Agency; 1976. EPA SW-119C.

5. Alternatives for hazardous waste management in the organic chemical, pesticides and explosives industries. Cincinnati, OH; U.S. Environmental Protection Agency; 1977. EPA SW-151C.

6. Assessment of industrial hazardous waste practices: electronic components manufacturing industry. Washington, DC; U.S. Environmental Protection Agency; 1977 January. 207 p. EPA SW-140C.

7. Assessment of industrial hazardous waste practices: special machinery manufacturing industries. Washington, DC; U.S. Environmental Protection Agency; 1977 March. 328 p. EPA SW-141C.

8. Background document, Resource Conservation and Recovery Act; Subtitle C -Identification and listing of hazardous waste; Section 261.31 and 261.32 - Listing of hazardous wastes. Washington, DC; U.S. Environmental Protection Agency; 1980 May 2.

9. Sampling and sampling procedures for hazardous waste streams. Cincinnati, OH; U.S. Environmental Protection Agency; 1980 January. 78 p. EPA-600/2-80-018.

10. Hazardous material incineration design criteria. Cincinnati, OH; U.S. Environmental Protection Agency; 1979 October. 110 p. EPA-600/2-79-198.

11. Duvall, D. S.; Rubey, W. A.; and Mescher, J. A. High temperature decomposition of organic hazardous waste. Treatment of hazardous waste, proceedings of the sixth annual research symposium. Cincinnati, OH; U.S. Environmental Protection Agency; 1980 March. p. 121-131. EPA-600/9-80-011.

12. Becker, K. P.; and C. J. Wall. Waste treatment advances: Fluid bed incineration of wastes. Chemical Engineering Progress. 72:61-68, 1976 October.

CHAPTER 4

INCINERATOR AND AIR POLLUTION CONTROL SYSTEM DESIGN EVALUATION

4.1 INTRODUCTION

This chapter presents engineering calculations and general "rules of thumb" that can be used to determine whether or not incinerator and air pollution control system design and operating criteria are consistent with good industry practice and sufficient to meet current emission standards. The evaluation procedures are intended to determine if (1) the physical, chemical, and thermodynamic properties of the waste have been properly considered in the incinerator and air pollution control device design; (2) the basic design considerations for these units have been addressed; (3) acceptable temperatures, residence times, oxygen concentrations, and mixing can be achieved and maintained in the incinerator; (4) air pollution control system design and operating criteria are in line with current industry practice and the desired degree of pollutant removal; (5) various components of the incinerator, air pollution control, and gas handling systems have sufficient capacity to handle the quantities of waste to be burned; (6) the design incorporates process control and automatic shutdown capability to minimize the release of hazardous material in the event of equipment malfunction; and (7) appropriate materials of construction are used.

Evaluation procedures are presented for two generic types of incinerators and three generic types of air pollution control devices: liquid injection incinerators, rotary kiln/afterburner incinerators, venturi scrubbers, packed bed scrubbers, and plate (or tray) tower scrubbers. While liquid injection incinerators are used only for disposal of liquid organic wastes, rotary kilns are used to dispose of both liquid and solid wastes. Venturi scrubbers are primarily used for particulate control, while packed bed and plate tower scrubbers are used for acid gas removal. It is believed that more than 90% of the hazardous waste incineration facilities in the United States employ these generic incinerator and air pollution control device designs. Electrostatic precipitators may be used for particulate removal at large incineration facilities. However, these devices are extremely difficult to evaluate from a theoretical standpoint; a compliance test is usually needed to ensure acceptable performance. If other types of incinerators and/or air pollution control devices are being evaluated technical assistance can be requested.

Incinerator and air pollution control system evaluation procedures are presented in Sections 4.3 and 4.4, respectively. Section 4.5 presents worksheets to simplify some of the calculations shown in 4.3 and 4.4.

The following section, 4.2, describes how the destruction and removal efficiency (DRE) of an incinerator/air pollution control system can be calculated for the principal organic hazardous constituent(s) (POHC) of a waste. The determination of how to designate POHC's is given in Section 2 of the Guidance Manual for Evaluating Permit Applications for the Operation of Incinerator Units. The current state-of-the-art in combustion modeling does not allow a purely theoretical prediction of destruction and removal efficiency based on design and operating parameters for the incinerator/air pollution control system. Therefore, the DRE calculations presented in Section 4.2 cannot be applied in preliminary design evaluation unless sampling and analysis data are available. However, destruction and removal efficiency calculations are an integral part of the final design evaluation process.

4.2 DESTRUCTION AND REMOVAL EFFICIENCY CALCULATIONS

4.2.1 Definition

Destruction and removal efficiency for an incinerator/air pollution control system is defined by the following formula:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} (100)$$

where DRE = destruction and removal efficiency, %

W_{in} = mass feed rate of the principal organic hazardous constituent(s) to the incinerator.

W_{out} = mass emission rate of the principal organic hazardous constituent(s) to the atmosphere (as measured in the stack prior to discharge.

Thus, DRE calculations are based on the combined efficiencies of destruction in the incinerator and removal from the gas stream in the air pollution control system. The (potential) presence of principal organic hazardous constituents in incinerator bottom ash or solid/liquid discharges from air pollution control devices is not accounted for in the DRE calculation as currently defined by EPA. Many previous trial burn tests determined only the "destruction efficiency". These tests ignored the contribution of the pollution control devices.

Part 264, Subpart O regulations for hazardous waste incineration require a DRE of 99.99% for all principal organic hazardous components of a waste unless it can be demonstrated that a higher or lower DRE is more appropriate based on human health criteria. Specification of the principal organic hazardous constituents in a waste is subject to best engineering judgment, considering the toxicity, thermal stability, and quantity of each organic waste constituent. DRE requirements in the Subpart O regulations do not apply to metals or other noncombustible materials.

Destruction and removal efficiencies are normally measured only during trial burns and occasional compliance tests, and are used as a basis for determining whether or not the incinerator/air pollution control system operating conditions are adequate. Sections 4.3 and 4.4 present design evaluation procedures for incinerators and air pollution control devices that are based on state-of-the-art engineering practice. However, any conclusions reached through these evaluation procedures should be supported by trial burn data demonstrating acceptable destruction and removal efficiency.

4.2.2 Sample Calculation

A liquid injection incinerator equipped with a quench tower, venturi scrubber, and packed bed caustic scrubber has been constructed to burn a mixture of waste oils and chlorinated solvents with the following empirical composition:

73.0 wt % carbon
16.5 wt % chlorine
10.5 wt % hydrogen

The principal organic hazardous components are trichloroethylene, 1,1,1-trichloroethane, methylene chloride, and perchloroethylene. Each of these compounds constitutes about 5% of the total waste feed to the incinerator.

During a trial burn, the incinerator was operated at a waste feed rate of 5,000 lb/hr and 50% excess air. The gas flow rate measured in the stack was 19,200 dscfm. Under these conditions, the measured concentrations of the principle organic hazardous components were:

Trichloroethylene - 4.9 μg/dscf
1,1,1-Trichloroethane - 1.0 μg/dscf
Methylene chloride - 49 μg/dscf
Perchloroethylene - 490 μg/dscf

In order to calculate destruction and removal efficiency for each of these compounds using the equation,

$$\text{DRE} = \frac{W_{in} - W_{out}}{W_{in}} (100)$$

it is necessary to calculate the mass flow of each component entering and exiting the system. Because each hazardous component constitutes about 5% of the waste and the total waste feed rate was 5,000 lb/hr, W_{in} for each component is:

$$W_{in} = 0.05 \text{ (5,000 lb/hr)} = 250 \text{ lb/hr}$$

The mass flow rate of each component exiting the stack is then calculated by the following equation:

$$W_{out} = C_i \times \left[\frac{(19{,}200 \text{ dscfm}) \ (60 \text{ min/hr})}{4.54 \times 10^8 \ \mu g/lb} \right]$$

where W_{out} = mass flow rate of component i exiting the stack, lb/hr

C_i = concentration of component i in the stack gas, µg/dscf

Using this equation to calculate W_{out} for each component and the previously cited equation for destruction and removal efficiency, the following results are obtained:

Component	W_{out}, lb/hr	DRE, %
Trichloroethylene	0.0124	99.995
1,1,1-Trichloroethane	0.00254	99.999
Methylene chloride	0.124	99.95
Perchloroethylene	1.24	99.5

These results indicate that the required 99.99% destruction and removal efficiency was achieved in the trial burn for trichloroethylene and 1,1,1-trichloroethane, but not for methylene chloride and perchloroethylene.

Worksheet #1 in Section 4.5 presents a generalized procedure for destruction and removal efficiency calculations.

4.3 INCINERATOR EVALUATION

A logic diagram for evaluating both liquid injection and rotary kiln incinerator designs and operating criteria is shown in Figure 4-1. It consists of six separate evaluation procedures intended to answer the following questions:

- Are the basic incinerator components properly incorporated in the design?
- Have the physical, chemical, and thermodynamic properties of the waste been properly considered in the incinerator design and proposed operating conditions?
- Are the proposed temperature/excess air/residence time combinations internally consistent and achievable? Can adequate turbulence and mixing be achieved under these conditions?
- Is the auxiliary fuel firing capacity acceptable?
- Does the design incorporate suitable combustion process control and safety shutdown interlocks?
- Are appropriate materials of construction employed?

Subsections 4.3.1 through 4.3.6 present background information and procedures for answering questions.

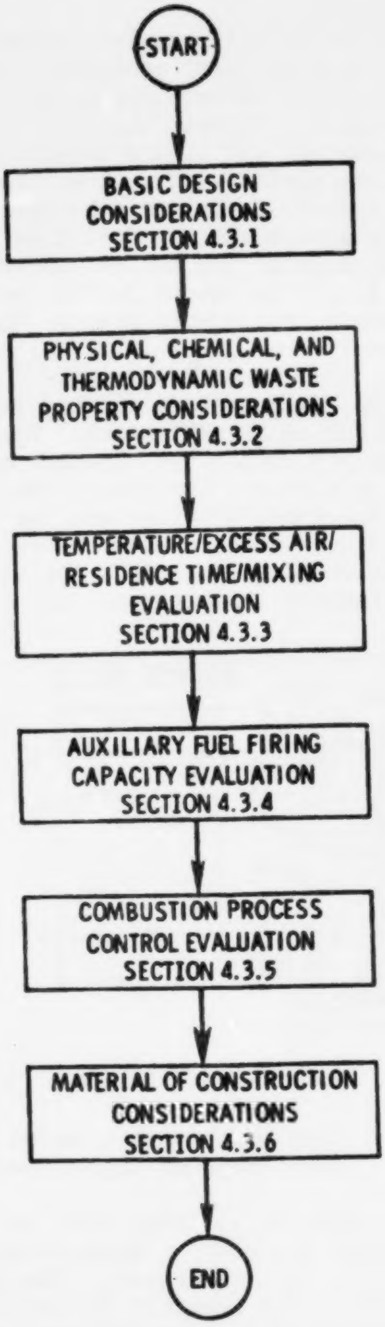

START
BASIC DESIGN CONSIDERATIONS SECTION 4.3.1
PHYSICAL, CHEMICAL, AND THERMODYNAMIC WASTE PROPERTY CONSIDERATIONS SECTION 4.3.2
TEMPERATURE/EXCESS AIR/ RESIDENCE TIME/MIXING EVALUATION SECTION 4.3.3
AUXILIARY FUEL FIRING CAPACITY EVALUATION SECTION 4.3.4
COMBUSTION PROCESS CONTROL EVALUATION SECTION 4.3.5
MATERIAL OF CONSTRUCTION CONSIDERATIONS SECTION 4.3.6
END

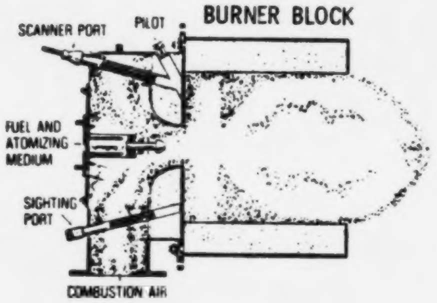
Figure 4-1. Incinerator design evaluation criteria.

4.3.1 Basic Design Considerations

4.3.1.1 Liquid Injection Incinerators--

Liquid injection incinerators are usually simple, refractory-lined cylinders (either horizontally or vertically aligned) equipped with one or more waste burners. Liquid wastes are injected through the burner(s), atomized to fine droplets, and burned in suspension. To heat the unit to operating temperature before waste is introduced, however, all liquid injection incinerator designs should also include an auxiliary fuel firing system. This may consist of separate burners for auxiliary fuel, dual-liquid burners, or single-liquid burners equipped with a premix system whereby fuel flow is gradually turned down and waste flow is increased after the desired operating temperature is attained. If auxiliary fuel firing is needed during routine operation the same types of systems are needed: fuel/waste premix, dual-liquid burners, or separate auxiliary fuel burners.

Each burner, regardless of type, is generally mounted in a refractory block or ignition tile (see Figure 4-2 for an illustration). This is necessary to confine the primary combustion air introduced through the burner, to ensure proper air/waste mixing, and to maintain ignition. The shape of the ignition tile cavity also affects the shape of the flame and the quantity of primary air which must be introduced at the burner. Some burners and tiles are arranged to aspirate hot combustion gases back into the tile, which aids in vaporizing the liquid and increasing flame temperature more rapidly.



"Reproduced courtesy of Trane Thermal Company, Conshohocken, Pa."

Figure 4-2. High heat release burner for combustion of liquid waste [1].

The dimensions of the burner block, or ignition tile, vary depending on the burner design. Each manufacturer has his own geometrical specifications, which have been developed through past experience. Therefore, it is not possible to specify a single burner block geometry for design evaluation purposes. However, this aspect of the design can be checked to eliminate systems that do not provide for any flame retention.

The location of each burner in the incinerator and its firing angle, relative to the combustion chamber, should also be checked. In axial or side-fired nonswirling units, the burner is mounted either on the end firing down the length of the chamber or in a sidewall firing along a radius. Such designs, while simple and easy to construct, are relatively inefficient in their use of combustion volume. Improved utilization of combustion space and higher heat release rates can be achieved with the utilization of swirl or vortex burners or designs involving tangential entry. Regardless of the burner location and/or gas flow pattern, however, the burner is placed so that the flame does not impinge on refractory walls. Impingement results in flame quenching, and can lead to smoke formation or otherwise incomplete combustion. In multiple burner systems, each burner should be aligned so that its flame does not impact on other burners.

Engineering judgment is used in predicting whether or not these undesirable phenomena will occur with a specific incinerator design.

4.3.1.2 Rotary Kiln Incinerators--
To insure complete waste combustion rotary kiln incinerator designs normally include an afterburner. The primary function of the kiln is to convert solid wastes to gases, which occurs through a series of volatilization, destructive distillation, and partial combustion reactions. However, an afterburner is almost always required to complete the gas-phase combustion reactions. The afterburner is connected directly to the discharge end of the kiln, whereby the gases exiting the kiln turn from a horizontal flow path to a vertical flow path upwards to the afterburner chamber. The afterburner itself may be horizontally or vertically aligned.

Both the afterburner and kiln are usually equipped with an auxiliary fuel firing system to bring the units up to the desired operating temperatures. As explained in Section 4.3.1.1 for liquid injection incinerators, the auxiliary fuel system may consist of separate burners for auxiliary fuel, dual-liquid burners designed for combined waste/fuel firing, or single-liquid burners equipped with a premix system, whereby fuel flow is gradually turned down and liquid waste flow is increased after the desired operating temperature is attained.

If liquid wastes are to be burned in the kiln and/or afterburner, additional considerations are:

- flame retention characteristics of the burners,
- burner alignment to avoid flame impingement on refractory walls, and
- in multiple burner systems, burner alignment to avoid interference with the operation of other burners.

These topics are discussed in Section 4.3.1.1 under liquid injection incinerator evaluation.

One difference between liquid injection incinerators and rotary kilns burning liquid wastes in conjunction with solids is that in the kiln liquid wastes may be fired either at the feed or discharge end of the unit. Cocurrent and countercurrent firing designs are both widely used.

4.3.2 Physical, Chemical, and Thermodynamic Waste Property Considerations

4.3.2.1 Liquid Injection Incinerators--

Before a liquid waste can be combusted, it must be converted to the gaseous state. This change from a liquid to a gas occurs inside the combustion chamber and requires heat transfer from the hot combustion gases to the injected liquid. To cause a rapid vaporization (i.e., increase heat transfer), it is necessary to increase the exposed liquid surface area. Most commonly the amount of surface exposed to heat is increased by finely atomizing the liquid to small droplets, usually to a 40 μM size or smaller. Good atomization is particularly important when high aqueous wastes or other low heating value wastes are being burned. It is usually achieved in the liquid burner directly at the point of air/fuel mixing.

The degree of atomization achieved in any burner depends on the kinematic viscosity of the liquid and the amount of solid impurities present. Liquids should generally have a kinematic viscosity of 10,000 SSU or less to be satisfactorily pumped and handled in pipes. For atomization, they should have a maximum kinematic viscosity of about 750 SSU. If the kinematic viscosity exceeds this value the atomization may not be fine enough. This may cause smoke or other unburned particles to leave the unit. However, this is only a rule of thumb. Some burners can handle more viscous fluids, while others cannot handle liquids approaching this kinematic viscosity.

Viscosity can be reduced by heating with tank coils or in-line heaters. However, 400-500°F (200-260°C) is normally the limit for heating to reduce viscosity, since pumping a hot tar or similar material becomes difficult above these temperatures. Should gases be evolved in any quantity before the desired viscosity is reached, they may cause unstable fuel feed and burning. If this occurs, the gases should be trapped and vented safely, either to the incinerator or elsewhere. Prior to heating a liquid waste stream, a check should also be made to insure that undesirable preliminary reactions such as polymerization, nitration, oxidation, etc., will not occur. If preheating is not feasible, based on these considerations, a lower viscosity and miscible liquid may be added to reduce the viscosity of the mixture; fuel oil for example.

Solid impurities in the waste can interfere with burner operation via pluggage, erosion, and ash buildup. Both the concentration and size of the solids, relative to the diameter of the nozzle, need to be considered. As discussed in Chapter 5, filtration may be employed to remove solids from the waste prior to injection through the burner.

Liquid waste atomization can be achieved by any of the following means:

- rotary cup atomization
- single-fluid pressure atomization
- two-fluid, low pressure air atomization
- two-fluid, high pressure air atomization
- two-fluid, high pressure steam atomization

In air or steam atomizing burners, atomization can be accomplished internally, by impinging the gas and liquid stream inside the nozzle before spraying; externally, by impinging jets of gas and liquid outside the nozzle; or by sonic means (see Figures 4-3 through 4-5). Sonic atomizers use compressed gas to create high frequency sound waves which are directed on the liquid stream. The liquid nozzle diameter is relatively large, and little waste pressurization is required. Some slurries and liquids with relatively large particles can be handled without plugging problems.

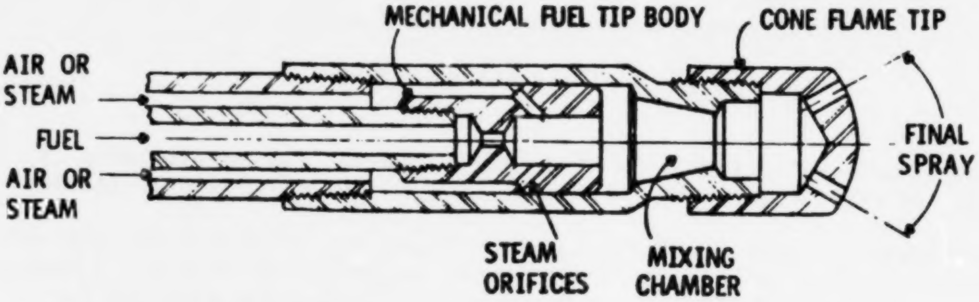

MECHANICAL FUEL TIP BODY
CONE FLAME TIP
AIR OR STEAM
FUEL
AIR OR STEAM
FINAL SPRAY
STEAM ORIFICES
MIXING CHAMBER

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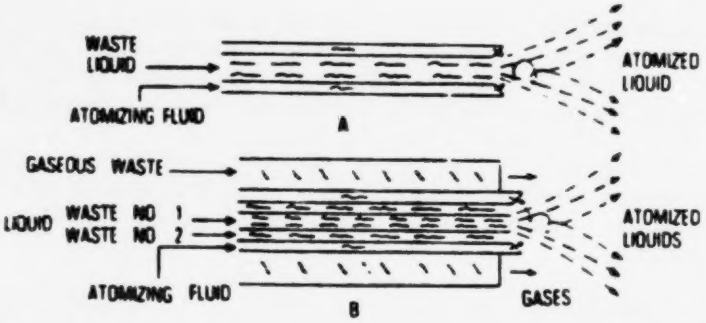
Figure 4-3. Internal mix nozzle [2].


WASTE LIQUID
ATOMIZING FLUID
ATOMIZED LIQUID
A
GASEOUS WASTE
LIQUID
WASTE NO 1
WASTE NO 2
ATOMIZING FLUID
ATOMIZED LIQUIDS
GASES
B

"Reproduced courtesy of Trane Thermal Company, Conshohocken, Pa."

Figure 4-4. External mix nozzles [1].

The rotary cup consists of an open cup mounted on a hollow shaft. The cup is spun rapidly and liquid is admitted through the hollow shaft. A thin film of the liquid to be atomized is centrifugally torn from the lip of the cup and surface tension reforms it into droplets. To achieve conically shaped flames an annular high velocity jet of air (primary air) must be directed axially around the cup. If too little primary air is admitted the fuel will impinge on the sides of the incinerator. If too much primary air is admitted the flame will not be stable and will be blown off the cup. For fixed firing rates, the proper adjustment can be found and the unit operated for long periods of time without cleaning. This requires little liquid pressurization and is ideal for

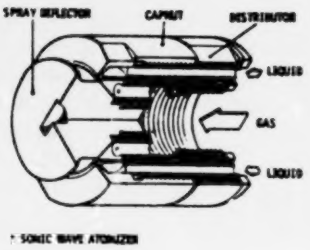


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Figure 4-5. Sonic atomizing nozzle [3].

atomizing liquids with relatively high solids content. Burner turndown is about 5:1 and capacities from 1 to 265 gal/hr, (1-280 cm^3/S) are available.

In single-fluid pressure atomizing nozzle burners, the liquid is given a swirl as it passes through an orifice with internal tangential guide slots. Moderate liquid pressures of 100-150 psi provide good atomization with low to moderate liquid viscosity. In the simplest form, the waste is fed directly to the nozzle but turndown is limited to 2.5 to 3:1 since the degree of atomization drops rapidly with decrease in pressure. In a modified form, involving a return flow of liquid, turndown up to 10:1 can be achieved.

When this type of atomization is used, secondary combustion air is generally introduced around the conical spray of droplets. Flames tend to be short, bushy, and of low velocity. Combustion tends to be slower as only secondary air is supplied and a larger combustion chamber is usually required.

Typical burner capacities are in the range of 10 to 105 gal/hr. Disadvantages of single-fluid pressure atomization are erosion of the burner orifice and a tendency toward pluggage with solids or liquid pyrolysis products, particularly in smaller sizes.

Two-fluid atomizing nozzles may be of the low pressure or high pressure variety, the latter being more common with high viscosity materials. In low pressure atomizers, air from blowers at pressures from 0.5 to 5 psig is used to aid atomization of the liquid. A viscous tar, heated to a viscosity of 15-18 centistokes, requires air at a pressure of somewhat more than 1.5 psig, while a low viscosity or aqueous waste can be atomized with 0.5 psig air. The waste liquid is supplied at a pressure of 4.5-17.5 psig. Burner turndown ranges from 3:1 up to 6:1. Atomization air required varies from 370 to 1,000 ft^3/gal of waste liquid. Less air is required as atomizing pressure is increased. The flame is relatively short as up to 40% of the stoichiometric air may be admixed with the liquid in atomization.

High pressure two-fluid burners require compressed air or steam at pressures from 30 to 150 psig. Air consumption is from 80 to 210 ft^3/gal of waste, and steam requirements may be 2.1 to 4.2 lb/gal with careful control of the operation. Turndown is relatively poor (3:1 or 4:1) and considerable energy is employed for atomization. Since only a small fraction of stoichiometric air is used for atomization, flames tend to be relatively long. The major advantage of such burners is the ability to burn barely pumpable liquids without further viscosity reduction. Steam atomization also tends to reduce soot formation with wastes that would normally burn with a smoky flame.

Table 4-1 identifies typical kinematic viscosity and solids handling limitations for the various atomization techniques. These data are based on a survey of 14 burner manufacturers. In evaluating a specific incinerator design, however, the viscosity and solids content of the wastes should be compared with manufacturer specifications for the particular burner employed.

TABLE 4-1. KINEMATIC VISCOSITY AND SOLIDS HANDLING LIMITATIONS OF VARIOUS ATOMIZATION TECHNIQUES

Atomization type	Maximum kinematic viscosity, SSU	Maximum solids mesh size	Maximum solids concentration
Rotary cup	175 to 300	35 to 100	20%
Single-fluid pressure	150		Essentially zero
Internal low pressure air ($\leq$30 psi)	100		Essentially zero
External low pressure air	200 to 1,500	200 (depends on nozzle ID)	30% (depends on nozzle ID)
External high pressure air	150 to 5,000	100 to 200 (depends on nozzle ID)	70%
External high pressure steam	150 to 5,000	100 to 200 (depends on nozzle ID)	70%

A procedure for evaluating whether or not a given burner atomization technique is suitable for the waste under consideration is presented in Table 4-2.

Chemical and thermodynamic properties of the waste that need to be considered in incinerator design evaluation are its elemental composition, its net heating value, and any special properties (e.g., explosive properties) that may interfere with incinerator operation or require special design considerations. The percentages of carbon, hydrogen, oxygen, nitrogen, sulfur, halogens, and phosphorus in the waste, as well as its moisture content, need to be known to calculate stoichiometric combustion air requirements and to predict combustion gas flow and composition[a]. In these calculations, the following reactions are assumed:

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[a] Air requirements, combustion gas flow, and gas composition form the basis for many subsequent evaluation procedures.

$$C + O_2 \rightarrow CO_2$$

$$H_2 + 1/2O_2 \rightarrow H_2O$$

$$H_2O \rightarrow H_2O$$

$$N_2 \rightarrow N_2$$

$$Cl_2 + H_2O \rightarrow 2HCl + 1/2O_2$$

$$F_2 + H_2O \rightarrow 2HF + 1/2O_2$$

$$Br_2 \rightarrow Br_2$$

$$I_2 \rightarrow I_2$$

$$S + O_2 \rightarrow SO_2$$

$$2P + 2.5O_2 \rightarrow P_2O_5$$

TABLE 4-2. EVALUATION PROCEDURE FOR PHYSICAL WASTE PROPERTY/ATOMIZATION TECHNIQUE COMPATIBILITY

1. Identify the atomization technique employed.
2. Identify the kinematic viscosity of the waste at the proposed injection temperature.
3. Check Table 4-1 and/or burner manufacturer specifications to determine if the waste viscosity and atomization technique are compatible.
4. Identify the solids content of the waste and the maximum size of the particles (after pretreatment, if any).
5. Check Table 4-1 and/or burner manufacturer specifications to determine if the solids content of the waste and the atomization technique are compatible.

Table 4-3 shows the stoichiometric or theoretical oxygen requirements and combustion product yields for each of these reactions. Once the weight fraction of each element in the waste has been determined, the stoichiometric oxygen requirements and combustion product yields can be calculated on a lb/lb waste basis. The stoichiometric air requirement is determined directly from the stoichiometric oxygen requirement via the weight fraction of oxygen in air.

Of course, the reactions listed above are not the only ones that occur in combustion processes. Carbon, carbon monoxide, free hydrogen, nitrogen oxides, free chlorine and fluorine, hydrogen bromide and iodide, sulfur trioxide, and

TABLE 4-3. STOICHIOMETRIC OXYGEN REQUIREMENTS AND COMBUSTION PRODUCTS YIELDS

Elemental waste component	Stoichiometric oxygen requirement	Combustion product yield
C	2.67 lb/lb C	3.67 lb CO_2/lb C
H_2	8.0 lb/lb H_2	9.0 lb H_2O/lb H_2
O_2	-1.0 lb/lb O_2	-
N_2	-	1.0 lb N_2/lb N_2
H_2O	-	1.0 lb H_2O/lb H_2O
Cl_2	-0.23 lb/lb Cl_2	1.03 lb HCl/lb Cl_2 -0.25 lb H_2O/lb Cl_2
F_2	-0.42 lb/lb F_2	1.05 lb HF/lb F_2 -0.47 lb H_2O/lb F_2
Br_2	-	1.0 lb Br_2/lb Br_2
I_2	-	1.0 lb I_2/lb I_2
S	1.0 lb/lb S	2.0 lb SO_2/lb S
P	1.29 lb/lb P	2.29 lb P_2O_5/lb P
Air N_2	-	3.31 lb N_2/lb $(O_2)_{stoich}$

Stoichiometric air requirement = 4.31 x $(O_2)_{stoich}$

hydrogen sulfide, among other compounds, are also formed to some extent when the corresponding elements are present in the waste or fuel being burned. However, these combustion product yields are usually small in comparison to the yields of the primary combustion products identified above, and need not be considered in gas flow scoping calculations. (They do, however, need to be considered to determine the potential products of incomplete combustion). For most organic wastes and fuels, nitrogen, carbon dioxide, and water vapor are the major combustion products. When excess air is factored into the combustion gas flow, oxygen also becomes a significant component of the gas. Excess air requirements are discussed in Section 4.3.3. Worksheet 4-2 can be used to calculate the stack gas composition for major components, e.g., N_2, O_2, CO_2, HCl, SO_2.

Exceptions to the aforementioned combustion stoichiometry can occur when highly chlorinated or fluorinated wastes are being burned and insufficient hydrogen is present for equilibrium conversion to the halide form. Since hydrogen halides are much more readily scrubbed from combustion gases than halogens themselves, sufficient hydrogen should be provided for this equilibrium conversion to take place. If the waste itself contains insufficient hydrogen, auxiliary fuel or steam injection is needed to supply the necessary hydrogen equivalents. The stoichiometric (absolute minimum) requirements are $\underline{\text{1 lb } H_2/}$ $\underline{\text{35.5 lb } Cl_2}$ and $\underline{\text{1 lb } H_2\text{/19 lb } F_2}$ in the waste.

Equilibrium between halogens and hydrogen halides in incinerator gases is given by:

$$X_2 + H_2O = 2HX + 1/2\ O_2$$

where X_2 represents any free halogen.

For chlorine, this expression becomes:

$$Cl_2 + H_2O = 2HCl + 1/2\ O_2$$

At equilibrium, the concentrations of Cl_2, H_2O, HCl, and O_2 in the combustion gas (at essentially atmospheric pressure) is given by:

$$K_p = \frac{(P_{HCl})^2\ (P_{O_2})^P}{(P_{Cl_2})\ (P_{H_2O})}$$

where K_p = equilibrium constant

P_i = partial pressure of ith component, atm

Figure 4-6 presents a plot of the equilibrium constant, K_p, vs. temperature for the conversion of Cl_2 to HCl. If the combustion temperature is known, K_p can be identified from Figure 4-6 and the following equation can be used to predict the extent of conversion of Cl_2 to HCl.

$$K_p = \frac{4x^2 P_{Cl_2i}\ (P_{O_2i} + 1/2x\ P_{Cl_2i})^{1/2}}{P_{H_2Oi}\ (1 - X)^2}$$

where x = fractional conversion of Cl_2

P_{Cl_2i}, P_{O_2i}, P_{H_2Oi} = calculated partial pressures of Cl_2, O_2, and H_2O assuming that all organic chlorine is converted to Cl_2 before the reaction to form HCl occurs.

In addition to the aforementioned waste constituents, metallic elements present in the waste influence the assessment of air pollution control requirements and materials of construction (e.g., refractory type). However, the metals content of a waste will not significantly affect the stoichiometric air requirements or combustion gas flow rate.

The heating value of a waste corresponds to the quantity of heat released when the waste is burned, commonly expressed as Btu/lb. Since combustion reactions are exothermic, all organic wastes have some finite heating value. However, the magnitude of this heating value must be considered in establishing an energy balance for the combustion chamber and in assessing the need for auxiliary fuel firing. To maintain combustion, the amount of heat released by the burning waste must be sufficient to heat incoming waste up to its ignition temperature and to provide the necessary activation energy for the combustion reactions to occur. Activation energy, expressed as Btu/lb or the equivalent,

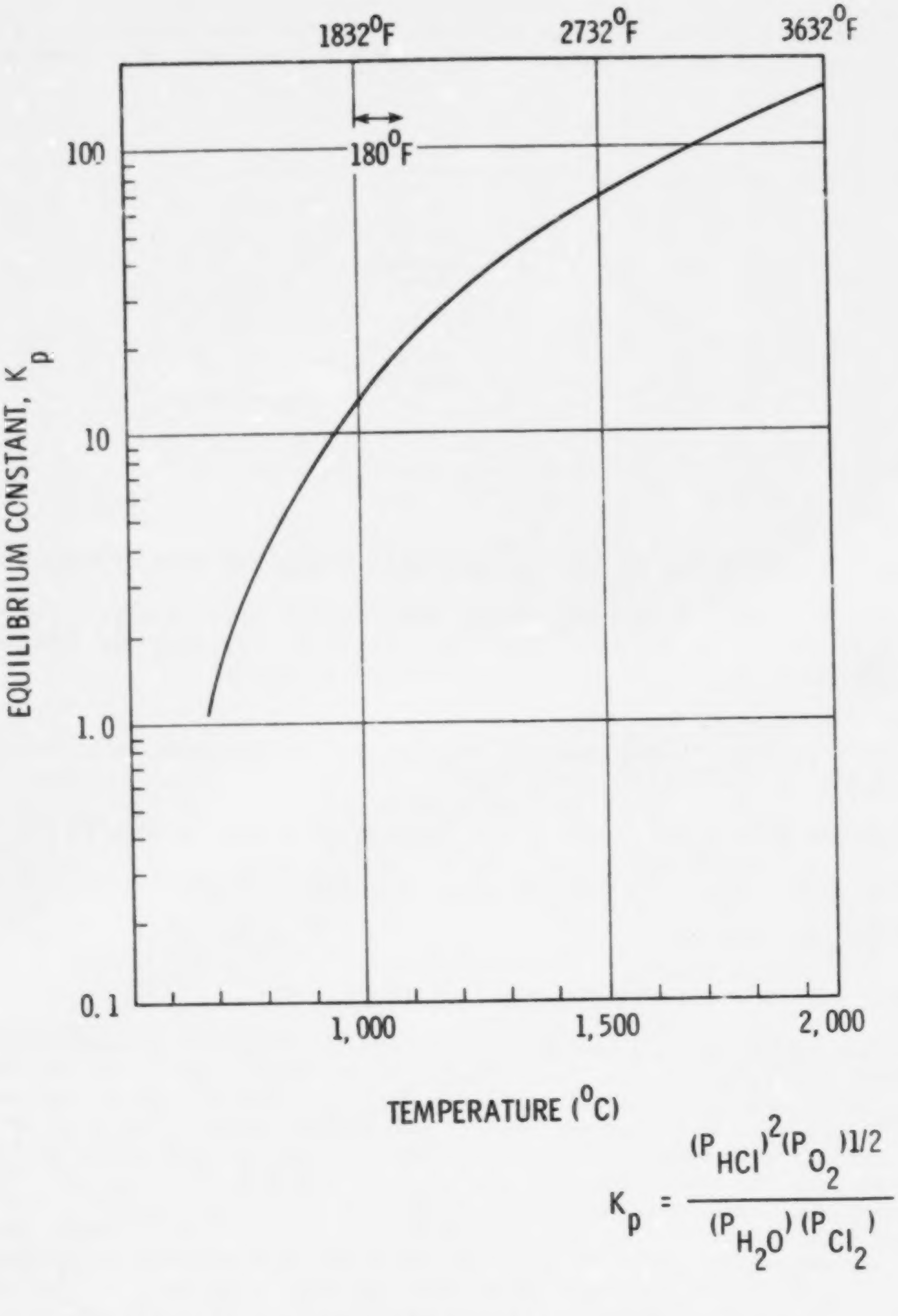


Figure 4-6. Equilibrium constant versus temperature.

is the quantity of heat needed to destabilize molecular bonds and create reactive intermediates so that the exothermic reaction with oxygen will proceed. Figure 4-7 shows the general relationship between activation energy and heating value.

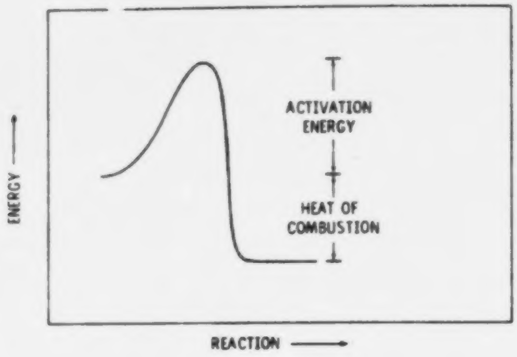


Figure 4-7. Relationship between activation energy and heat of combustion.

Note: The diagram is simplified in the sense that it shows a single activation energy for the reaction. Reactions with more than one intermediate have correspondingly more activation energy levels.

Waste heating values needed to sustain combustion without auxiliary fuel firing depend on the following criteria:

- physical form of the waste (i.e., gaseous vs. liquid vs solid),
- temperature required for refractory waste component destruction,
- excess air rate, and
- heat transfer characteristics of the incinerator.

In general, higher heating values are required for solids vs liquids vs gases, for higher operating temperatures, and for higher excess air rates, if combustion is to be sustained without auxiliary fuel consumption. Gases can sustain combustion at heating values as low as 3,000 Btu/lb, while 4,500 to 5,500 Btu/lb may be considered minimum heating value requirements for combustion of liquid wastes in high efficiency burners [1]. Figures 4-8 and 4-9 illustrate the relationship of adiabatic temperature to heating value for several levels of excess air for liquid wastes and gaseous wastes, respectively. Higher heating values are needed for solid wastes, but the requirements depend on particle size, and thus, the area available for heat and mass transfer. In the hazardous waste incineration industry, it is common practice to blend wastes (and fuel oil, if necessary) to an overall heating value of 8,000 Btu/lb.

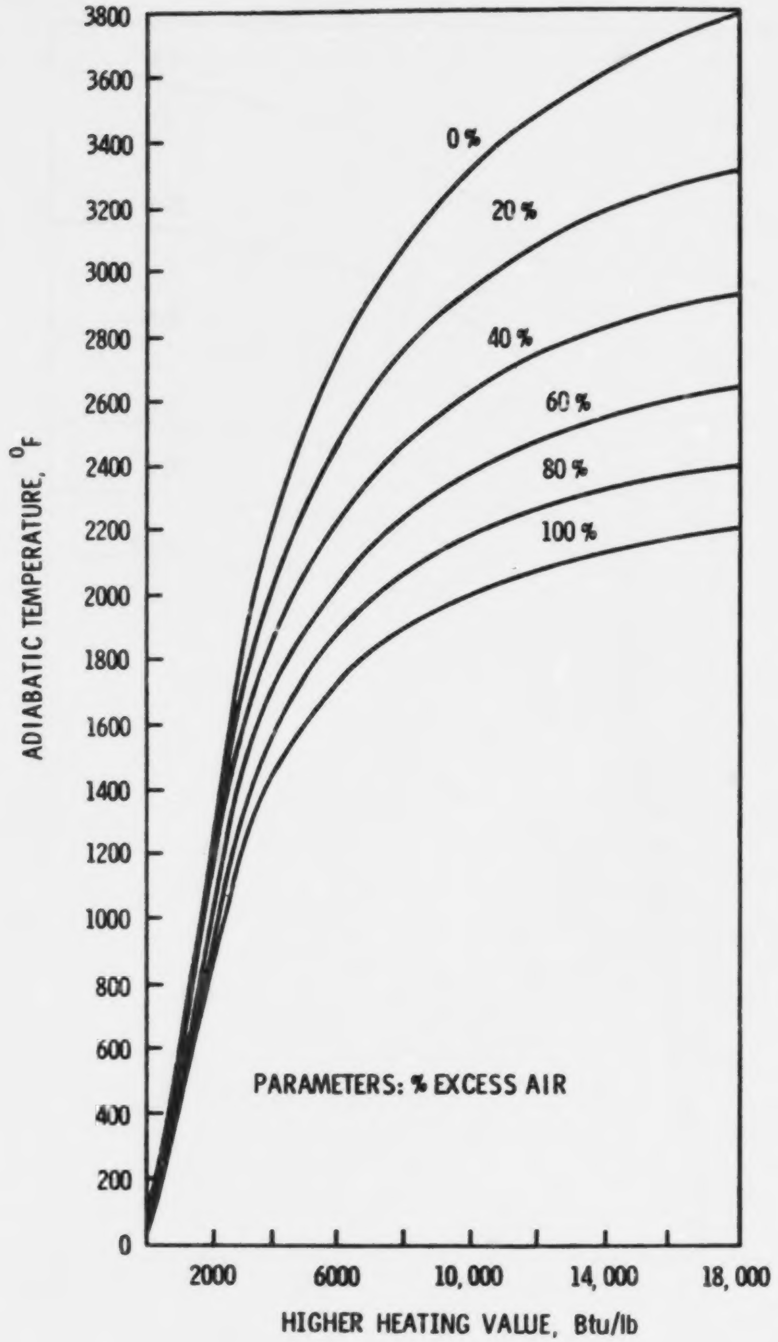


Figure 4-8. Adiabatic temperature of combustion gases from typical liquid wastes [1].

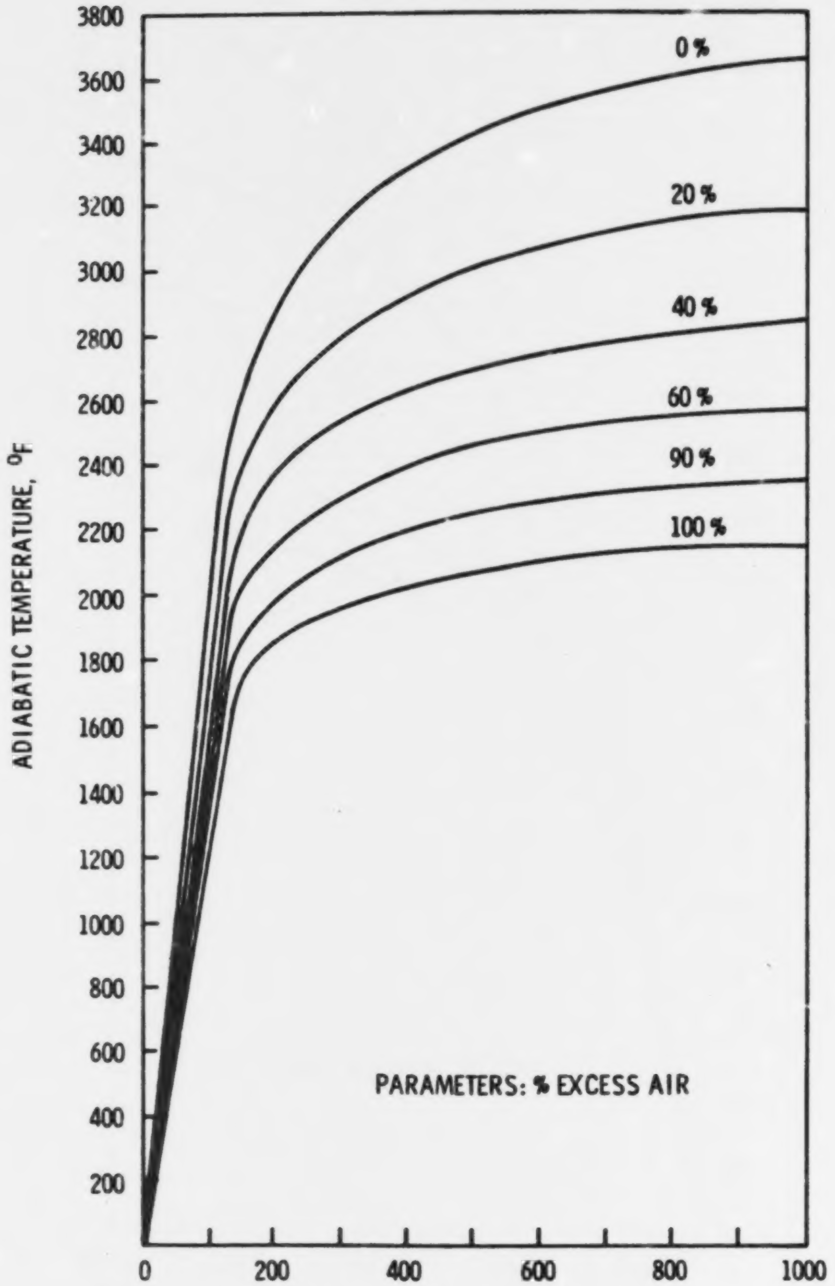
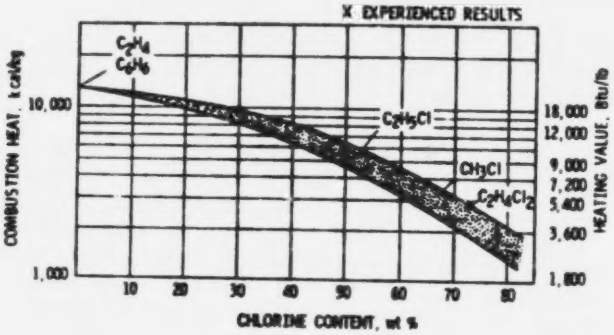


Figure 4-9. Adiabatic temperature of combustion gases from typical gaseous wastes [1].

When an organic waste exhibits a low heating value, it is usually due to high concentrations of moisture or halogenated compounds. Since water is an ultimate oxidation product, it has no heating value. In fact, a portion of the heat generated by combustion of the organic waste fraction is consumed in vaporizing and heating the moisture up to incinerator temperature. Therefore, an increase in the moisture content of an organic waste proportionately decreases the overall heating value on a Btu/lb waste basis.

The heating value of a waste also decreases as the chlorine (or other halogen) content increases, although there is no simple mathematical relationship. Figure 4-10 shows an empirical relationship between heating value and chlorine content for pure substances. At chlorine contents of 70% or greater, auxiliary fuel is needed to maintain combustion. Auxiliary fuel may also be required for less highly chlorinated waste unless high efficiency burners are used.



"Reproduced courtesey of Trane Thermal Company, Conshohockon, Pa."

Figure 4-10. Heat of combustion of chlorinated hydrocarbons [4].

In hazardous waste incineration, it is common practice to blend wastes so that the chlorine content does not exceed 30%. This is done to maintain sufficient heating value for sustained combustion and to limit free chlorine concentration in the combustion gas.

When heating value data are reported for a given waste, it is desirable to know whether they are "higher heating values," "lower heating values," or "net heating values." The difference between the higher heating value and lower heating value of a material is that the higher value includes the heat of condensation of water formed in the combustion reaction. The higher heating value of a material is sometimes called its "gross heating value." In the combustion of methane, for example, the higher heating value is based on the following stoichiometry:

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(\ell)}$$

where the subscripts g and ℓ represent gaseous and liquid states, respectively. The lower heating value is based on:

$$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}$$

The net heating value of a waste is determined by subtracting from its lower heating value the energy necessary to vaporize any moisture present in the waste initially. Thus, high aqueous wastes may exhibit a negative net heating value. Since this quantity represents the true energy input to the combustion process, only net heating values should be used in developing energy balances for incinerators.

The heating value of a complex waste mixture is difficult to predict *a priori*. Therefore, these values should be measured experimentally. Since heating values measured using oxygen bomb calorimeters are higher heating values, conversion to the net heating value is required for energy balance calculations. Worksheet 4-3 in Section 4.5 shows how this conversion is performed. Approximate net heating values for common auxiliary fuels are:

Residual fuel oil (e.g., No. 6) - 17,500 Btu/lb
Distillate fuel oil (e.g., No. 2) - 18,300 Btu/lb
Natural gas - 19,700 Btu/lb (1,000 Btu/scf)

Special characteristics of a waste such as extreme toxicity, mutagenicity or carcinogenicity, corrosiveness, fuming, odor, pyrophoric properties, thermal instability, shock sensitivity, and chemical instability should also be considered in incinerator facility design. Thermal or shock instability is of particular concern from a combustion standpoint, since wastes with these properties pose an explosion hazard. Other special properties relate more directly to the selection of waste handling procedures and air pollution control requirements. If potentially explosive wastes are encountered, technical assistance is advised.

Table 4-4 presents a procedure for chemical and thermodynamics waste property evaluation.

4.3.2.2 Rotary Kiln Incinerators--

When liquid wastes are to be burned in the kiln or afterburner, the kinematic viscosity of the liquid and its solids concentration and solids particle size must be considered to determine whether or not good atomization can be achieved with the proposed burner design. This subject is addressed in subsection 4.3.2.1 under liquid injection incinerator evaluation. The procedure outlined in Table 4-2, along with the discussion preceding this table, can be used to check physical waste property/burner compatibility for rotary kiln incinerators burning liquid wastes.

Although liquid wastes are frequently incinerated in rotary kilns, kilns are primarily designed for combustion of solid wastes. They are exceedingly versatile in this regard, capable of handling slurries, sludges, bulk solids of varying size, and containerized wastes. The only wastes that create problems in rotary kilns are (1) aqueous organic sludges that become sticky on drying and form a ring around the kiln's inner periphery, and (2) solids (e.g., drums) that tend to roll down the kiln and are not retained as long as the bulk of solids. To reduce this problem, drums and other cylindrical

TABLE 4-4. CHEMICAL AND THERMODYNAMIC WASTE PROPERTY EVALUATION PROCEDURE

1. Identify the elemental composition and moisture content of the waste and record this information on Worksheet 4-2 for future reference.

2. Does the waste contain chlorinated or fluorinated materials? (If YES, proceed to checkpoint #3. If NO, proceed to checkpoint #5.)

3. Is sufficient hydrogen present in the waste for equilibrium conversion of chlorine and fluorine to hydrogen chloride and hydrogen fluoride, respectively? See aforementioned evaluation criteria in Section 4.3.2.1. (If YES, proceed to checkpoint #5. If NO, proceed to checkpoint #4.)

4. Is auxiliary fuel firing or steam injection employed to provide the necessary hydrogen equivalents?

5. Identify the major components of the combustion gas, based on the elemental composition of the waste, that need to be considered in subsequent material and energy balance calculations. See Worksheet 4-2 for the recommended procedure. This procedure also determines the stoichiometric air requirement and combustion gas flow, which will be needed for subsequent evaluation procedures.

6. Determine the net heating value of the waste. Worksheet 4-3 shows how the net heating value can be calculated when higher heating values are known.

7. Does it appear likely that the waste will sustain combustion, based on its net heating value? (If YES, proceed to checkpoint #9. If NO, proceed to the following checkpoint.)

8. Is auxiliary fuel to be burned in conjunction with the waste?

9. Is the waste potentially explosive when exposed to high temperature or shock?

containers are usually not introduced to the kiln when it is empty. Other solids in the kiln help to impede the rolling action.

The major design checkpoint for rotary kiln/physical waste property compatibility is the type(s) of solid waste feed systems employed. These feed systems are discussed in Chapter 5.

Chemical and thermodynamic properties of the waste that need to be considered in rotary kiln design evaluation are its elemental composition, its net heating value, and any special properties (e.g., explosive properties, extreme toxicity) that may interfere with incinerator operation or require special design considerations. These are essentially the same properties that must be considered in liquid injection incinerator evaluation. Therefore, the background discussion in Section 4.3.2.1 and the evaluation procedure presented in Table 4-4 can be used for rotary kilns as well as liquid injection incinerators with some modifications.

The first modification relates to the calculation procedures for stoichiometric air requirement, combustion gas flow and composition. These calculations are more complex for rotary kiln incinerators because (a) liquid and solid wastes may be fed simultaneously to the kiln, and (b) liquid wastes and auxiliary fuel may be fed to the kiln,afterburner, or both. Therefore, Worksheet 4-4 (See Section 4-5) should be used instead of Worksheet 4-2 for combustion gas flow calculations. Worksheet 4-3 can still be used to calculate net heating values.

The second modification relates to the consideration of special waste properties. As discussed in Section 4.3.2.1 for liquid injection incinerators, technical assistance may be required if wastes with explosive properties are encountered. For rotary kilns, technical assistance is also advised if extremely toxic, mutagenic, or carcinogenic wastes are to be burned. This recommendation is based on the fact that kilns are much more prone to release of fugitive emissions than are liquid injection incinerators.

Unlike liquid injection incinerators which have no moving parts, rotary kiln designs incorporate high temperature seals between the stationary end plates and rotating section. These seals are inherently difficult to maintain airtight, which creates the potential for release of unburned wastes. Rotary kilns burning hazardous wastes are almost always operated at negative pressure to circumvent this problem, however, difficulties can still arise when batches of waste are fed semi-continuously. When drums containing relatively volatile wastes are fed to the kiln, for example, extremely rapid gas expansion occurs. This results in a positive pressure surge at the feed end of the kiln (even though the discharge end may still be under negative pressure), which forces unburned waste out through the end plates seals. This phenomenon is known as "puffing", and can pose a major problem if extremely toxic or otherwise hazardous materials are being burned.

Fugitive emissions can also exit the kiln through the feed chute if improperly designed. Therefore, the design of the solid waste feed system is an extremely important consideration in evaluating rotary kiln incinerators. This topic is addressed in Chapter 5.

4.3.3 Temperature, Excess Air, Residence Time, and Mixing Evaluation

Temperature, residence time, oxygen concentration, and the degree of air/waste mixing achieved are the primary variables affecting combustion efficiency in any incinerator design. The theoretical significance of these interrelated variables is discussed in the following subsection under "Liquid Injection Incinerators." Subsection 4.3.3.2 addresses additional temperature, time, excess air, and mixing considerations for rotary kilns.

In general, two major factors are involved in evaluating these variables as they relate to incinerator design. The first factor is whether or not the temperature, residence time, and excess air level, along with the degree of mixing achieved in the incinerator, are adequate for waste destruction. The second factor is whether or not the proposed operating conditions are achievable, since temperature, excess air, residence time, and mixing are all interrelated.

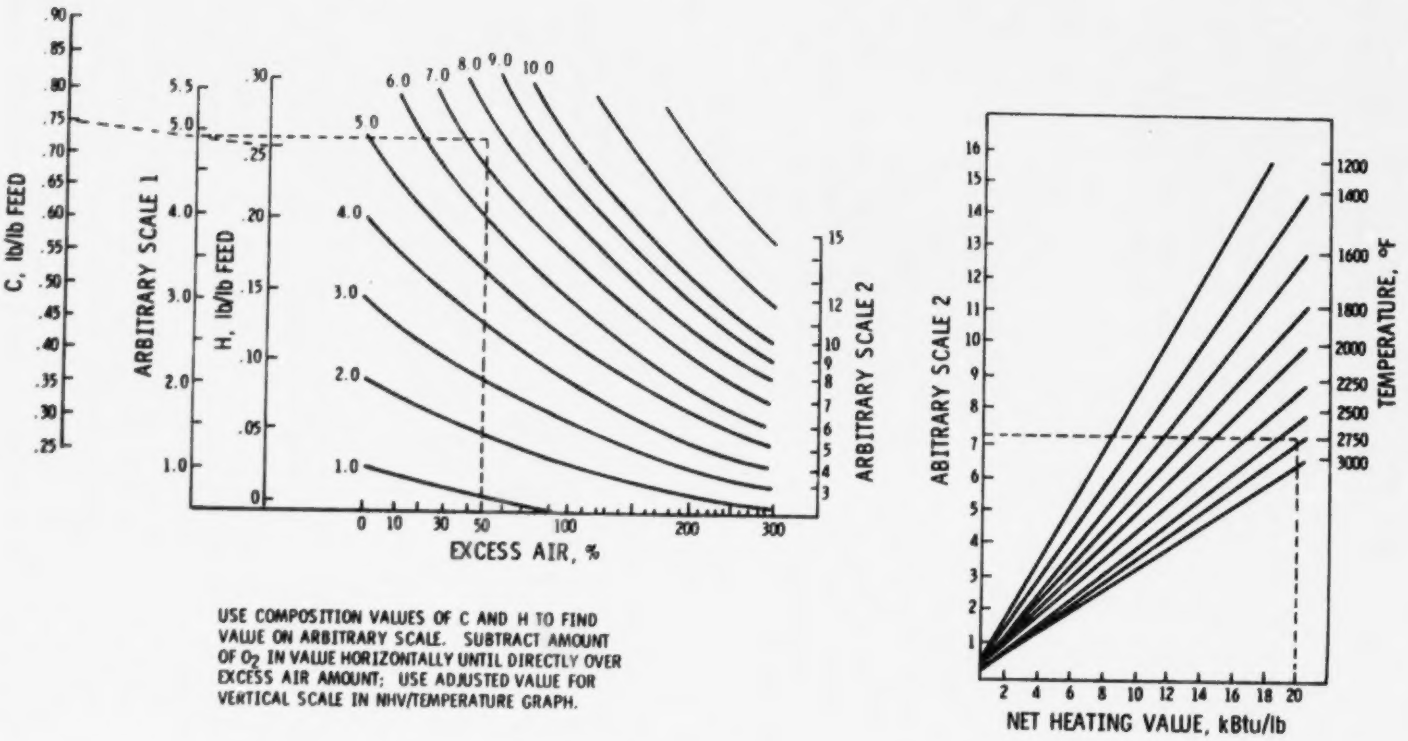
At the current state of the art, the adequacy of incinerator operating conditions can only be determined by past experience with the waste or by actual testing. Therefore, this factor is not addressed per se in the following subsections. The major focus of the following evaluation procedures is on whether or not a proposed set(s) of operating conditions is achievable. Basically, this involves a series of internal consistency checks.

4.3.3.1 Liquid Injection Incinerators--

The most basic requirement of any combustion system is a sufficient supply of air to completely oxidize the feed material. The stoichiometric, or theoretical air requirement is calculated from the chemical composition of the feed material, as shown in Section 4.3.2. If perfect mixing could be achieved and liquid waste burnout occurred instantaneously, then only the stoichiometric requirement of air would be needed. Neither of these phenomena occur in real-world applications, however, so some excess air is always required to ensure adequate waste/air contact. Excess air is usually expressed as a percentage of the stoichiometric air requirement. For example, 50% excess air implies that the total air supplied to the incinerator is 50% greater than the stoichiometric requirement.

The amount of excess air used or needed in a given application depends on the degree of air/waste mixing achieved in the primary combustion zone, process-dependent secondary combustion requirements, and the desired degree of combustion gas cooling. Since excess air acts as a diluent in the combustion process, it reduces the temperature in the incinerator (e.g., maximum theoretical temperatures are achieved at zero percent excess air). This temperature reduction is desirable when readily combustible, high heating value wastes are being burned in order to limit refractory degradation. When high aqueous or other low heating value waste is being burned, however, excess air should be minimized to keep the system temperature as high as possible. Even with highly combustible waste, it is desirable to limit excess air to some extent so that combustion chamber volume and downstream air pollution control system capacities can be limited.

Figure 4-11 maybe used to check the internal consistency of the proposed excess air rate and temperature, as long as the amount of carbon, hydrogen, and oxygen in the stream and its net heating value are known. To use the figure, first find the weight fraction of carbon on the scale marked C (on the far left) and the weight fraction of hydrogen on scale H. Connect these two points with a ruler and read the value at its intersection with arbitrary scale 1. Subtract the weight fraction of oxygen in the feed stream from this number. Plot this value on the middle graph, using arbitrary scale 1 as the vertical axis and the excess air scale as the horizontal axis. Interolate between the set of curves to find a value for arbitrary scale 2, which is then plotted on the vertical axis of the right-hand graph, with the net heating value of the feed plotted on the horizontal axis to determine the combustion gas temperature.



USE COMPOSITION VALUES OF C AND H TO FIND VALUE ON ARBITRARY SCALE. SUBTRACT AMOUNT OF O_2 IN VALUE HORIZONTALLY UNTIL DIRECTLY OVER EXCESS AIR AMOUNT; USE ADJUSTED VALUE FOR VERTICAL SCALE IN NHV/TEMPERATURE GRAPH.

Figure 4-11. Nomograph for checking the internal consistency of proposed excess air rate and combustion temperature in hazardous waste incinerators.

For example, suppose methane (CH_4-75% carbon, 25% hydrogen; net heating value of 19,700 Btu/lb) is burned with 50% excess air. Connecting 0.75 on the C scale with 0.25 on the H gives 4.9 at the intersection with arbitrary scale 1. Using this value and 50% excess air gives 7.25 on the middle graph. Plotting 7.25 vertically and 19.7 KBtu/lb horizontally on the right-hand graph shows a temperature of 2,700°F. If a temperature of 2,000°F is desired and excess air is to be calculated, plotting 19.7 kBtu/lb and 2,000°F gives 9.8 on arbitrary scale 2. Then using the middle graph, 9.8 on arbitrary scale 2 and 4.9 on arbitrary 1 shows an excess air rate of 100%. Figure 4-11 is accurate so long as the combustion gases consist of air, CO_2 and H_2O, i.e., the wastes consist mainly of carbon, hydrogen, and oxygen. The latter part of this section describes the procedures for more accurate calculations.

In liquid injection incinerators, two excess air rates must be considered: (1) the excess air present in the primary combustion air introduced through the burner, and (2) the total excess air, which includes secondary combustion air. Normally 10% to 20% excess air (i.e., 1.1 to 1.2 times the stoichiometric requirement) is supplied to the burner to prevent smoke formation in the flame zone. When relatively homogeneous wastes are being burned in high efficiency burners, 5% excess air may be adequate. Too much excess air through the burner is also undesirable, since this can blow the flame away from its retention cone. Burner manufacturer specifications are the best source of information for analysis.

In general, the total excess air rate should exceed 20% to 25% to insure adequate waste/air contact in the secondary combustion zone. However, the minimum requirement for a given incinerator depends on the degree of mixing achieved and waste specific factors.

Four basic questions should be considered in evaluating whether or not a proposed operating temperature is sufficient for waste destruction:

(1) Is the temperature high enough to heat all waste components (and combustion intermediates) above their respective ignition temperatures and to maintain combustion?

(2) Is the temperature high enough for complete reaction to occur at the proposed residence time?

(3) Is this temperature within normal limits for the generic design and/or attainable under the other proposed operating conditions?

(4) At what point in the combustion chamber is the proposed temperature to be measured?

Complete waste combustion requires a temperature, and heat release rate, in the incinerator high enough to raise the temperature of the incoming waste constituents above their respective ignition temperatures (i.e., to provide energy input in excess of their respective activation energies). In cases where combustion intermediates are more stable than the original waste constituents, higher temperatures are required for complete combustion of the intermediates than for parent compound destruction.

Since heat transfer, mass transfer, and oxidation all require a finite length of time, temperature requirements must also be evaluated in relation to the proposed residence time in the combustion chamber. Heat transfer, mass transfer, and kinetic reaction rates all increase with increasing temperature, lowering the residence time requirements. For extremely short residence times, however, temperatures higher than those needed for ignition may be required to complete the combustion process.

The current state of the art in combustion modeling does not allow a purely theoretical determination of temperature and residence time requirements for waste and combustion intermediate destruction. Therefore, the only reasonable alternative is an examination of temperature/residence time combinations used to destroy the same or similar waste in a similar or identical incinerator.

After addressing the temperature requirements for waste destruction, it is reasonable to determine whether or not the proposed temperature is within normal limits for the generic incinerator design and whether or not this temperature can be attained under the proposed firing conditions. Generally, liquid injection incinerator temperatures range from 1,400°F to 3,000°F depending on the generic design, type of waste being burned, and location within the combustion chamber. Usually 1,400°F is the minimum temperature needed to avoid smoke formation. A more typical hazardous waste incineration temperature is 1,800°F, although temperatures of 2,000°F to 2,200°F or higher are usually employed for halogenated aromatic wastes.

The question of whether or not the proposed temperature and excess air rate are attainable can be resolved by approximate calculations based on a heat balance around the combustion chamber. Figure 4-12 shows the heat inputs and outputs for the combustion chamber.

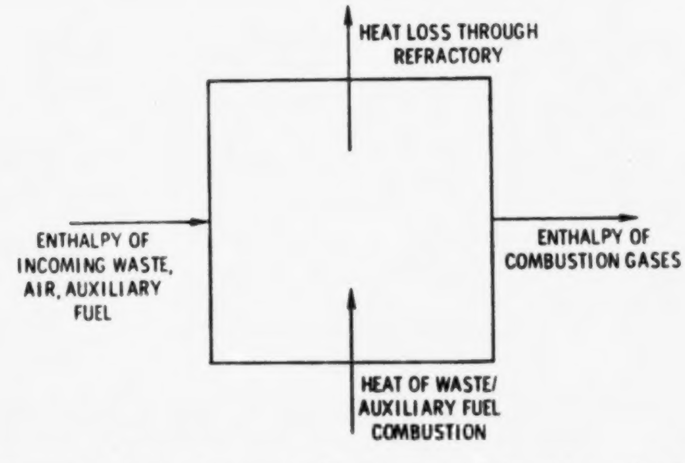

HEAT LOSS THROUGH REFRACTORY
ENTHALPY OF INCOMING WASTE, AIR, AUXILIARY FUEL
ENTHALPY OF COMBUSTION GASES
HEAT OF WASTE/ AUXILIARY FUEL COMBUSTION

Figure 4-12. Energy balance for combustion chamber.

Since liquid waste incineration is a steady state (or quasi-steady state) process, the enthalpy of the waste/auxiliary fuel/combustion air feed plus the heat released by combustion must equal the enthalpy of the combustion gases leaving the unit plus the heat loss through the refractory walls. This yields the general relationship:

$$\left(\begin{array}{c}\text{Heat loss}\\ \text{through refractory}\end{array}\right) = \left(\begin{array}{c}\text{Enthalpy of}\\ \text{incoming feed}\end{array}\right) + \left(\begin{array}{c}\text{Heat released by}\\ \text{combustion}\end{array}\right) - \left(\begin{array}{l}\text{Enthalpy}\\ \text{of combus-}\\ \text{tion gases}\end{array}\right)$$

or

$$Q = \Delta H$$

where Q = heat loss through refractory, Btu/lb waste
ΔH = overall enthalpy change in the combustion chamber, Btu/lb waste

Since enthalpy is a thermodynamic state function, the overall enthalpy change can be represented by any series of incremental enthalpy changes, so long as the initial state and final state correspond to the incinerator inlet and outlet conditions, respectively. The key is to select an enthalpy change pathway that simplifies the calculations involved, such as that shown in Figure 4-13.

Using this approach, the overall energy balance equation becomes:

$$Q = \Delta H = \Delta H_{1-2} + \Delta H_{2-3} + \Delta H_{3-4}$$

where ΔH_{j-k} = incremental enthalpy changes, Btu/lb waste

In Figure 4-13, the first enthalpy change, ΔH_{1-2}, represents the difference in feed enthalpy between injection temperature and standard conditions of 77°F (25°C). This term is seldom significant unless the combustion air is preheated to high temperature.

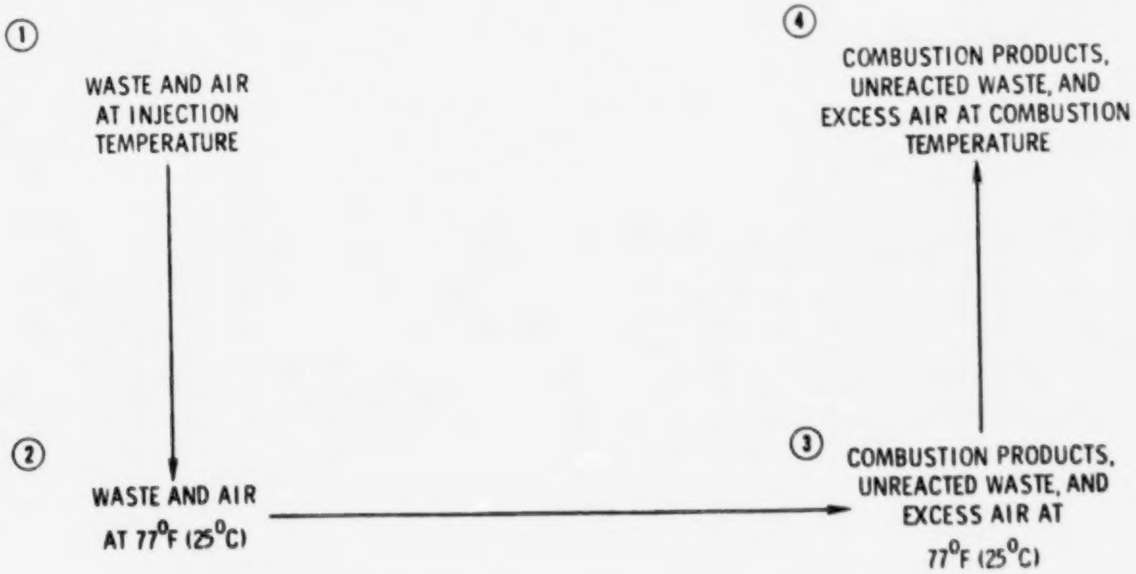

①
WASTE AND AIR AT INJECTION TEMPERATURE
④
COMBUSTION PRODUCTS, UNREACTED WASTE, AND EXCESS AIR AT COMBUSTION TEMPERATURE
②
WASTE AND AIR AT 77°F (25°C)
③
COMBUSTION PRODUCTS, UNREACTED WASTE, AND EXCESS AIR AT 77°F (25°C)

Figure 4-13. Enthalpy balance for combustion processes.

The term ΔH_{2-3} represents the heat released by combustion at isothermal conditions of 25°C. This corresponds to the way in which heats of combustion are measured and presented in the literature. The third term, ΔH_{3-4}, represents the difference in combustion product enthalpy between 25°C and the temperature at the combustion chamber outlet.

In mathematical terms, these incremental enthalpy changes are expressed as:

$$\Delta H_{1-2} = \sum_{\substack{i=1\\ \text{waste}\\ \text{components}}}^{k} n_i \overline{C_{pi}}(77 - T_{in})$$

$$+ 4.31\, \overline{C_p}_{air} (77 - T_{air})(O_2)_{stoich}(1 + EA)$$

$$\Delta H_{2-3} = \sum_{\substack{i=1\\ \text{reactive}\\ \text{waste}\\ \text{components}}}^{k} n_i X_i (\Delta H_c)_{i_{77°F}}$$

and

$$\Delta H_{3-4} = \left\{ \sum_{\substack{i=1\\ \text{reaction}\\ \text{products}}}^{k} n_i \overline{C_{pi}} X_i + \sum_{\substack{i=1\\ \text{reactive}\\ \text{waste}\\ \text{components}\\ \text{remaining}}}^{k} n_i \overline{C_{pi}}(1 - X_i)\right.$$

$$+ 4.31\, \overline{C_p}_{air}(O_2)_{stoich}(EA) \left[1 + \sum_{\substack{i=1\\ \text{reactive}\\ \text{components}}}^{k} n_i\left(1 - X_i\right)\right]$$

$$\left. + \sum_{\substack{i=1\\ \text{inert}\\ \text{waste}\\ \text{components}}}^{k} n_i \overline{C_{pi}} \right\} (T_{out} - 77)$$

where n_i = lb ith component/lb waste
$\overline{C_{pi}}$ = mean heat capacity of ith component over the temperature range involved, Btu/lb °F
T_{in} = waste injection temperature, °F
T_{air} = air inlet temperature, °F
X_i = fractional conversion of ith component (X_i = 1.0 at 100% combustion of ith component)
$(\Delta H_c)_{i_{77°F}}$ = heat of combustion of ith component at 77°F (25°C), Btu/lb
T_{out} = temperature at the combustion chamber outlet, °F
$(O_2)_{stoich}$ = stoichiometric oxygen requirement, lb O_2/lb waste
EA = excess air, %/100

To determine whether or not the proposed temperature/excess air combination is achievable, it is necessary to specify the desired temperature and calculate the corresponding excess air rate for comparison with the proposed value. However, there are far too many unknowns in these equations to solve for EA.

These equations can be simplified considerably by assuming that the combustion reactions go to essentially 100% completion.[a] With this assumption, the overall energy balance reduces to:

$$Q = \overline{C_p}_{\,waste}(77 - T_{in}) + 4.31\,\overline{C_p}_{\,air}(77 - T_{air})(O_2)_{stoich}(1 + EA)$$

$$+ (-\,NHV)_{77°F} + (T_{out} - 77)\left[\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products}}}^{k} n_i\,\overline{C_{pi}} + 4.31\,\overline{C_p}_{\,air}(O_2)_{stoich}EA\right]$$

where NHV = net heating value of the waste, Btu/lb

From the empirical waste composition (carbon content, hydrogen content, etc.), proposed excess air rate, and combustion stoichiometry discussed in Section 4.3.2, all the variables in this equation are fixed except the outlet temperature or excess air rate, mean heat capacities of the combustion gases, and the heat loss through the walls of the combustion chamber. To avoid rigorous heat transfer calculations, this heat loss can be assumed to be about 5% of the heat released in the combustion chamber, based on operating experience with hazardous waste incinerators. With this assumption, the energy balance reduces to:

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[a] Acceptance of the proposed temperature/residence combination should ensure combustion efficiencies close enough to 100% for this value to be used in heat balance calculations.

$$\overline{C_p}_{\text{waste}}(77 - T_{in}) + 4.31\ \overline{C_p}_{\text{air}}(77 - T_{air})(O_2)_{\text{stoich}}(1 + EA) + 0.95\ (-\text{NHV})$$

$$+ \left[\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products}}}^{k} n_i\ \overline{C_{pi}} + 4.31\ \overline{C_p}_{\text{air}}(O_2)_{\text{stoich}}EA \right] (T_{out} - 77) = 0$$

from which the first two terms can be deleted if neither waste nor air preheating is employed. (The waste enthalpy term can almost always be deleted anyway.) This yields:

$$0.95\ (-\text{NHV}) + \left[\sum_{\substack{i=1 \\ \text{combustion} \\ \text{products}}}^{k} n_i\ \overline{C_{pi}} + 4.31\ \overline{C_p}_{\text{air}}(O_2)_{\text{stoich}}EA \right] (T_{out} - 77) = 0$$

The mean heat capacities of the combustion gases will vary to a small degree depending on the incinerator outlet temperature. For the purposes of approximate calculations, however, the following values can be assumed:

Gas component	$\overline{C_p}$, Btu/lb °F
Excess air	0.26
N_2	0.26
CO_2	0.26
H_2O	0.49
HCl	0.20
SO_2	0.18

This yields the expression[a]:

$$0.95\ (-\text{NHV}) + \Big[0.26\ (n_{N_2} + n_{CO_2}) + 0.49\ N_{H_2O}$$

$$+ 1.12\ (O_2)_{\text{stoich}}EA \Big] (T_{out} - 77) = 0$$

---

[a] The term n_{N_2} in this equation refers to the nitrogen present in the combustion gases under stoichiometric conditions. It does not include excess air nitrogen.

for wastes containing only carbon, hydrogen, oxygen, and nitrogen. If other gas components, constitute more than a few percent of the total flow, additional heat capacity terms must be added.

If auxiliary fuel is to be burned in conjunction with the waste, a modification of the previous equation is needed. This is as follows:

$$0.95\,(-\,\mathrm{NHV})_{\text{waste}} + n_{\text{fuel}}(-\,\mathrm{NHV})_{\text{fuel}} + \left[\sum_{\substack{i=1\\ \text{waste}\\ \text{combustion}\\ \text{products}}}^{k} n_i\,\overline{C_{pi}} + n_{\text{fuel}} \sum_{\substack{i=1\\ \text{fuel}\\ \text{combustion}\\ \text{products}}}^{k} (n_{i\ \text{fuel}}\,\overline{C_{pi}}) + 4.31\,\overline{C_p}_{\text{air}}(O_2)_{\text{stoich}}\text{EA}\right](T_{\text{out}} - 77) = 0$$

where $n_{i\ \text{fuel}}$ = lb ith combustion gas component/lb fuel

$\overline{C}_{p\ \text{fuel}}$ = mean heat capacity of fuel over the applicable temperature range, Btu/lb °F

$\mathrm{NHV}_{\text{fuel}}$ = heating value of fuel, Btu/lb

n_{fuel} = lb fuel/lb waste

If only carbon, hydrogen, oxygen, and nitrogen are present, the equation can be simplified to[a]:

$$0.95\left[(-\mathrm{NHV})_{\text{waste}} + n_{\text{fuel}}\,(-\mathrm{NHV})_{\text{fuel}}\right]$$

$$+\left[0.26\,(n_{N_2} + n_{CO_2}) + 0.49\,n_{H_2O} + 1.12\,(O_2)_{\text{stoich}}\,\text{EA}\right](T_{\text{out}} - 77) = 0$$

---

[a] In this equation, n_{N_2}, n_{CO_2}, n_{H_2O}, $(O_2)_{\text{stoich}}$, and EA apply to the combined waste/auxiliary fuel mix, and n_{N_2} accounts refers to the nitrogen present in the combustion gases under stoichiometric conditions.

By fixing the outlet temperature at the proposed value, the equations shown above can be used to estimate the maximum achievable excess air rate for comparison with that proposed. Thus, the equations provide an internal consistency check for proposed temperature/excess air combinations. Worksheet 4-5 in Section 4-5 shows how the calculation can be performed in a step-by-step manner.

When identifying a minimum temperature acceptable for waste destruction, it is also important to identify the location in the combustion chamber at which this temperature should be measured. Temperature varies tremendously from one point to another in the combustion chamber, being highest in the flame and lowest at the refractory wall or at a point of significant air infiltration (e.g., in the vicinity of secondary air ports). Ideally, temperature should be measured in the bulk gas flow at a point after which the gas has traversed the combustion chamber volume that provides the specified residence time for the unit. It should not be measured at a point of flame impingement or at a point directly in sight of radiation from the flame. Chapter 5 discusses temperature measurement in more detail.

A comprehensive evaluation procedure for temperature/excess air considerations is shown in Table 4-5.

In addition to temperature and excess air, residence time is a key factor affecting the extent of combustion. This variable, also referred to as retention time or dwell time, is the mean length of time that the waste is exposed to the high temperatures in the incinerator. It is important in designing and evaluating incinerators because a finite amount of time is required for each step in the heat transfer/mass transfer/reaction pathway to occur.

In liquid waste combustion, discrete (although short) time intervals are required for heat transfer from the gas to the surface of the atomized droplets, liquid evaporation, mixing with oxygen in the gas stream, and reaction, which itself involves a series of individual steps depending on the complexity of the waste's molecular structure. The total time required for these processes to occur depends on the temperature in the combustion zone, the degree of mixing achieved, and the size of the liquid droplets. Residence time requirements increase as combustion temperature is decreased, as mixing is reduced, and/or as the size of discrete waste particles is increased. Typical residence times in liquid injection incinerators range from 0.5 s to 2.0 s.

Gas residence times are defined by the following formula:

$$\theta = \int_0^V \frac{dV}{q}$$

where θ = mean residence time, s
V = combustion chamber volume, ft^3
q = gas flow rate, ft^3/s within the differential volume, dv

and gas flow rate is given by:

$$q = \left(\frac{0.79}{y_{N_2}}\right)\left(\frac{T + 460}{528}\right)\left[4.31\ (O_2)_{\text{stoich } 68°F}\right](1 + EA)$$

where y_{N_2} = mole fraction N_2 in the gas within the differential volume

T = gas temperature, °F, within the differential volume

$(O_2)_{\text{stoich}}$ = stoichiometric oxygen requirement, scf/s

EA = excess oxygen fraction, %/100, within the differential volume

As indicated in this equation, residence time is not an independent variable. For an incinerator of fixed volume and relatively constant feed, residence time is influenced by the temperature and excess air rate employed.

Gas flow rate at any point along the length of the combustion chamber is a function of the temperature at that point, the amount of excess air added up to that point, and the extent to which the combustion reactions are completed at that point. Therefore, solution of the above equation requires a knowledge of the temperature profile, excess air profile, and waste conversion profile along the combustion chamber. These factors must be expressed as functions of combustion chamber length (i.e., volume) in order for the integration to be performed.

Since this detailed information can rarely, if ever, be determined with a reasonable degree of accuracy, an alternate approach is normally adopted. In this approach, the flow rate, q, is specified at the desired operating temperature (measured at the incinerator outlet) and total excess air rate. The equation is then simplified to:

$$\theta = \frac{V}{q_{out}}$$

The chamber volume used in this calculation is an estimated value, corresponding to the volume through which the combustion gases flow after they have been heated to the desired operating temperature. Thus, the chamber volume used in residence time calculations should be at least somewhat less than the total volume of the chamber. However, an upper bound residence time can be estimated by:

$$\theta_{max} = \frac{V_T}{q_{out}}$$

where V_T = total volume of the chamber

Any residence times calculated by this equation should only be used for general comparison purposes.

In the preceding discussion, all equations apply to the nominal, or mean, residence time in the combustion chamber. A thoroughly rigorous approach would require tracer studies to determine residence time distributions in the incinerator. However, nominal residence times are sufficient for evaluation purposes, so long as the incinerator design is such that significant channeling (analogous to dead space in the combustion chamber) does not occur. Channeling is usually prevented by creating abrupt changes in flow direction or by establishing a definite flow pattern in the combustion chamber (e.g., cyclonic flow).

TABLE 4-5. TEMPERATURE/EXCESS AIR EVALUATION PROCEDURE.

1. Identify the proposed operating temperature.

2. Is this temperature sufficient to convert all waste components to their ultimate oxidation products, assuming that adequate residence time, oxygen, and mixing are provided? See the preceding discussion (Section 4.3.3.1) for general guidelines. Outside sources of information can be consulted for waste-specific data.

3. Identify the excess primary combustion air rate proposed in the permit application.

4. Does this excess air rate meet or exceed the general requirements identified in the preceding discussion and/or burner manufacturer specifications?

5. Identify the total excess air rate proposed.

6. Is this excess air rate acceptable? General guidelines are presented in Section 4.3.3.1.

7. Independently calculate the total excess air rate needed to maintain the proposed operating temperature (see Worksheet 4-5).

8. Is this calculated excess air rate greater than or comparable to the proposed total excess air rate? (If YES, proceed to checkpoint #11. If NO, proceed to the following checkpoint).

9. Is this excess air rate acceptable, even though it is less than the proposed excess air rate? See the preceding discussion for general guidelines. (If YES, proceed to checkpoint #11. If NO, proceed to the following checkpoint.)

10. Are there any mechanical restraints in the system that would prevent increasing the auxiliary fuel-to-waste firing ratio (which would be needed to maintain both an acceptable temperature and excess air rate)? If necessary, repeat the calculations shown in Worksheet 4-5 for the maximum achievable fuel-to-waste ratio.

(continued)

TABLE 4-5 (continued)

11. Identify the location at which temperature is to be measured in the incinerator.

12. Is this location (a) suitable based on the considerations in the preceding discussion or (b) comparable to the location at which temperature was measured during an appropriate prior test?

Table 4-6 presents a gas residence time evaluation procedure which can be used in conjunction with the evaluation procedure for temperature and excess air shown in Table 4-5, since all three variables are interrelated.

TABLE 4-6. GAS RESIDENCE TIME EVALUATION PROCEDURE

1. Identify the proposed gas residence time.

2. Does this residence time appear adequate, considering the proposed operating temperature and excess air rate, and assuming that good mixing is achieved? See the preceding discussion for general guidelines and the appendices for specific information.

3. Does the proposed residence time appear to be achievable? See Worksheet 4-6.

Temperature, oxygen, and residence time requirements for waste destruction all depend to some extent on the degree of mixing achieved in the combustion chamber. This parameter is difficult to express in absolute terms, however. Many of the problems involved in interpreting burn data relate to the difficulty involved in quantifying the degree of mixing achieved in the incinerator, as opposed to the degree of mixing achieved in another incinerator of different design.

In liquid waste incinerators, the degree of mixing is determined by the specific burner design (i.e., how the primary air and waste/fuel are mixed), combustion product gas and secondary air flow patterns in the combustion chamber, and turbulence. Turbulence is related to the Reynolds number for the combustion gases, expressed as:

$$Re = \frac{Dv\rho}{\mu}$$

where D = combustion chamber diameter, ft
v = gas velocity, ft/s
ρ = gas density, lb/ft^3
μ = gas viscosity, lb/ft s

Turbulent flow conditions exist at Reynold's numbers of approximately 2,300 and greater. Below this Reynold's number laminar or transition flow prevails and mixing occurs only by diffusion.

In conventional liquid injection incinerators or afterburners, it is possible to simplify the Reynold's number to consideration of superficial gas velocity only. Adequate turbulence is usually achieved at superficial gas velocities of 10 to 15 ft/s. Superficial gas velocities are determined by

$$v = \frac{q}{A}$$

where q = gas flow rate at operating temperature, ft^3/s
A = cross-sectional area of the incinerator chamber, ft^2

When primary combustion air is introduced tangentially to the burner (e.g., vortex burners), secondary air is introduced tangentially, or burner alignment is such that cyclonic flow prevails in the incinerator, actual gas velocities exceed the superficial velocity. Thus, adequate turbulence may be achieved at superficial velocities less than 10 ft/s in cyclonic flow systems. However, the tradeoff is difficult to quantify. Turbulence can also be increased by installing baffles in the secondary combustion zone of the incinerator, which abruptly change the direction of gas flow. However, this also increases pressure drop across the system and is not a common practice in liquid injection incinerator design. Steam jets can also be used to promote turbulence.

Table 4-7 presents a procedure for evaluating the mixing characteristics of liquid injection incinerators. Since mixing is related to the gas flow rate through the incinerator, this evaluation procedure can be used in conjunction with that for temperature and excess air, which affect gas flow independent of the waste feed rate.

TABLE 4-7. MIXING EVALUATION PROCEDURE

1. Calculate the superficial gas velocity in the incinerator chamber at operating temperature (see Worksheet 4-7).
2. Does this velocity meet or exceed the general guidelines provided above (i.e., 10-15 ft/s)?
3. If not, is cyclonic flow or some mechanical means of enhancing turbulence designed into the system? If YES, somewhat lower superficial velocities than those listed above may still provide suitable mixing.

4.3.3.2 Rotary Kiln Incinerators--

In rotary kiln/afterburner incineration systems, three excess air rates must be considered: (1) excess air present in the primary combustion air introduced through liquid waste burners in the kiln or afterburner section, (2) total excess air fed to the kiln, and (3) the excess air percentage maintained in the afterburner.

Normally, 10% to 20% excess air (i.e., 1.1 to 1.2 times the stoichiometric requirement) must be supplied to liquid waste burners to prevent smoke formation in the flame zone. When relatively homogeneous wastes are being burned in high efficiency burners, 5% excess air may be adequate. Too much excess air through the burner is also undesirable, since this can blow the flame away from its retention cone. Burner manufacturer specifications are the best source of information for case-by-case analysis.

As stated in Section 4.3.3.1, 20% to 25% total excess air is a practical minimum for liquid injection incinerators to achieve adequate air/waste contact. Higher excess air rates are needed in rotary kilns, however, because the efficacy of air/solids contact is less than that for air and atomized liquid droplets. Typical excess air rates range from 140% to 210% or greater, depending on the desired operating temperature and the heating value of the waste. When high aqueous wastes are being burned, lower excess air rates may be needed to maintain adequate temperature. However, less than 100% excess air in the kiln may not provide adequate air/solids contact.

Since it is usually desirable to maintain the afterburner at a higher temperature than the kiln, and because only liquid wastes or auxiliary fuel is fired in the afterburner, the excess air rate in the afterburner is usually less than that in the kiln. In a typical system operating at 1,500°F in the kiln and 1,800°F in the afterburner, approximately 160% to 170% excess air would be maintained in the afterburner compared to ~210% in the kiln. Considering 100% excess air in the kiln as a practical minimum, approximately 80% excess air or more should be maintained in the afterburner. This includes air contained in the kiln exit gases as well as air introduced in the afterburner itself, and is based on the total stoichiometric oxygen requirement for all wastes and fuels burned in the system.

In evaluating temperature requirements for a rotary kiln/afterburner system, seven basic questions should be considered:

(1) Is the temperature in the kiln high enough to volatilize, partially oxidize, or otherwise convert all organic components of the waste to a gaseous state?

(2) Is this temperature high enough for the aforementioned processes to occur within the proposed solids retention time?

(3) Is the afterburner temperature high enough to heat all volatilized wastes (and combustion intermediates) above their respective ignition temperatures and maintain combustion?

(4) Is the temperature high enough for complete reaction to occur within the proposed afterburner residence time?

(5) Is the kiln operating temperature within normal limits and/or attainable under the other proposed operating conditions?

(6) Is the afterburner temperature within normal limits and/or attainable under the other proposed operating conditions?

(7) At what points in the system are the temperatures to be measured?

The current state-of-the-art in combustion modeling does not allow a purely theoretical determination of time and temperature requirements for solid waste burnout or combustion in the gas phase. Therefore, the only reasonable alternative is an examination of temperature/time combinations used to destroy the same or similar waste in a similar or identical rotary kiln/afterburner system. This information is needed to address questions 1 through 4 above. The latter three questions are addressed in the following paragraphs.

Temperatures in rotary kiln incinerators usually range from about 1,400°F to 3,000°F, depending on the types of waste being burned and the location in the kiln. Common operating temperatures, measured outside of the flame zone, are 1,500°F to 1,600°F. The question of whether or not these or other proposed temperatures are attainable at the proposed excess air rate can be resolved by approximate calculations based on a heat balance around the kiln (see Section 4.3.3.1 for a discussion of how heat balances are formulated).

The difficulty that arises in this calculation is that the extent of combustion, or actual heat release compared to the maximum attainable heat release, is unknown. However, the maximum achievable excess air rate in the kiln at the specified operating temperature can still be estimated by assuming complete combustion. This corresponds to a worst case analysis. The maximum calculated excess air rate must exceed the proposed excess air rate, or the specified operating temperature will not be attainable.

The applicable heat balance equation for the kiln, assuming complete combustion is shown on the following page.

This equation is also based on the assumptions that (a) heat loss through the kiln walls is about 5% of the heat released on combustion, and (b) waste preheating, if employed, will result in negligible heat input compared to the heat released on combustion (which is almost always the case). This equation can be solved directly for EA, the maximum attainable excess air rate in the kiln, once the desired operating temperature is specified. Mean heat capacities for common combustion gas components, applicable over temperature ranges normally encontered, are shown in Section 4.3.3.1.

Worksheet 4-8 in Section 4-5 presents a step-by-step calculation procedure.

$$4.31\ \overline{C_p}\ \text{air}\ (77-T_{air})(O_2)_{stoich(k)}(1+EA_k) - 0.95\left(\frac{n_1NHV_1 + n_2NHV_2 + n_{fK}HV_{fK}}{1+n_{fK}}\right) + \left[\sum_{\substack{i=1\\ \text{combustion}\\ \text{products}\\ \text{from kiln}}}^{k} n_i\ \overline{C_{pi}} + 4.31\ \overline{C_p}\ \text{air}(O_2)_{stoich}EA_k\right](T_{out} - 77) = 0$$

where $\overline{C_{pi}}$ = mean heat capacity of ith component over the temperature range involved, Btu/lb °F

T_{air} = air preheat temperature, °F

$(O_2)_{stoich}$ = total stoichiometric oxygen requirement for wastes and auxiliary fuel fed to the kiln, lb O_2/lb feed

EA_k = percent excess air/100(in kiln)

n_1 = lb liquid waste/lb waste

n_2 = lb solid waste/lb waste

n_{fK} = lb fuel/lb waste

NHV_1 = net heating value of liquid waste, Btu/lb

NHV_2 = net heating value of solid waste, Btu/lb

HV_{fK} = net heating value of fuel, Btu/lb

n_i = lb ith combustion product/lb feed

T_{out} = desired temperature at the kiln outlet, °F

When no combustion air preheating is employed, this equation simplifies to:

$$-0.95\left(\frac{n_1NHV_1 + n_2NHV_2 + n_{fK}HV_{fK}}{1+n_{fK}}\right) + \left[\sum_{\substack{i=1\\ \text{combustion}\\ \text{products}\\ \text{from kiln}}}^{k} n_i\ \overline{C_{pi}} + 4.31\ \overline{C_p}\ \text{air}(O_2)_{stoich}EA_k\right](T_{out} - 77) = 0$$

Using the heat capacities presented in Section 4.3.3.1, and assuming that CO_2, H_2O, N_2, and O_2 are the only significant components of the combustion gas, the equation further simplifies to[a]:

$$-0.95\left(\frac{n_1 NHV_1 + n_2 NHV_2 + n_{fK} HV_{fK}}{1 + n_{fK}}\right) + \left[0.26 \quad n_{CO_2} + n_{N_2} \quad + 0.49\ n_{H_2O} + 1.12\ (O_2)_{stoich}\right] EA_K \quad (T_{out} - 77) = 0$$

Excess air in the afterburner can be estimated in similar fashion, after the desired operating temperature is specified. In this calculation, heat inputs to and from the entire system (kiln and afterburner) are considered. The resulting heat balance equation is shown below.

This equation is also based on assumptions of 5% heat loss from the system and negligible energy input due to waste/auxiliary fuel or air preheating. Worksheet 4-9 presents a step-by-step calculation procedure.

$$-0.95\left(\frac{\dfrac{n_1 NHV_1 + n_2 NHV_2 + n_{fK} HV_{fK}}{1 + n_{fK}} + n_{AK}\ \dfrac{NHV_3 + n_{fA} HV_{fA}}{1 + n_{fA}}}{1 + n_{AK}}\right)$$

$$+ \left[\frac{\overset{k}{\underset{\substack{i=1\\ \text{combustion}\\ \text{products}\\ \text{from kiln}}}{}} \quad n_{iK}\ \overline{C_{pi}} + n_{AK} \quad \overset{k}{\underset{\substack{i=1\\ \text{combustion}\\ \text{products}\\ \text{afterburner}\\ \text{feed}}}{}} \quad n_{iA}\ \overline{C_{pi}}}{1 + n_{AK}}\right] (T_{out} - 77)$$

$$+ 4.31\ \overline{C_p}\ \text{air}\left[(O_2)_{stoich(K)} + (O_2)_{stoich(A)}\right] EA \quad (T_{out} - 77) = 0$$

where $(O_2)_{stoich(A)}$ = stoichiometric oxygen requirement for waste and auxiliary fuel fed to the afterburner, lb O_2/lb feed

EA = percent excess air/100(in afterburner)

n_{AK} = lb afterburner feed/lb kiln feed

NHV_3 = net heating value of liquid waste fed to the afterburner, Btu/lb

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[a] The term n_{N_2} in this equation relates to the nitrogen present in the combustion gas under stoichiometric conditions. It does not include excess air nitrogen.

n_{fA} = lb fuel/lb waste in afterburner

HV_{fA} = heating value of auxiliary fuel burned in the afterburner, Btu/lb

n_{iK} = lb ith combustion product from kiln/lb kiln feed

n_{iA} = lb ith combustion product from afterburner feed/lb afterburner feed

T_{out} = desired afterburner outlet temperature, °F

Once the major components of the combustion gas have been identified (CO_2, H_2O, N_2, and O_2 in most cases), the latter two terms in this equation can be simplified by substituting in the heat capacities reported in Section 4.3.3.1. A similar substitution is shown on the preceding page for the rotary kiln heat balance equation.

When quantifying the desired temperatures in the kiln and afterburner, it is also important to fix the locations at which these temperatures should be measured. Temperature varies tremendously from one point to another in each unit, being highest in the flame and lowest at the refractory wall or at a point of significant air infiltration (e.g., in the vicinity of secondary air ports, end plate seals, and feed chute). Ideally, temperatures should be measured in the bulk gas flow at a point after which the gas has traversed the volume of each chamber that provides its specified residence time. Temperatures should not be measured at a point of flame impingement or at a point directly in sight of radiation from the flame. Temperature measurement is discussed in more detail in Chapter 5.

An evaluation procedure for temperature/excess air considerations is shown in Table 4-8.

In rotary kiln incineration systems, both the solids retention time in the kiln and the gas residence time in the afterburner must be considered. Afterburner residence time considerations are essentially the same as those for liquid injection incinerators, a topic which is addressed in Section 4.3.3.1. Therefore, the following discussion focuses primarily on solids retention time estimates. For a discussion of gas residence time estimates and corresponding evaluation procedures, see Section 4.3.3.1.

Solids retention times in rotary kilns are a function of the length-to-diameter ratio of the kiln, the slope of the kiln, and its rotational velocity. The functional relationship between these variables is [5]:

$$\theta = 0.19\ (L/D)/SN$$

where θ = retention time, min
L = kiln length, ft
D = kiln diameter, ft
S = kiln slope, ft/ft
N = rotational velocity, rpm

TABLE 4-8. TEMPERATURE/EXCESS AIR EVALUATION PROCEDURE FOR ROTARY KILN/AFTERBURNER INCINERATORS

1. Identify the proposed kiln and afterburner operating temperatures.

2. Is the kiln temperature sufficient for complete solid waste burnout, assuming that adequate retention time, excess air, and mixing are provided? This determination must be based on operating experience and/or other burn data.

3. Is the afterburner temperature sufficient to complete the combustion reactions, assuming that adequate residence time, excess air, and mixing are provided? See the preceding discussion (Section 4.3.3.2) for general guidelines.

4. Identify the excess primary air rates for each liquid waste burner in the kiln or afterburner.

5. Does this excess air rate meet or exceed the general requirements identified in the preceding discussion and/or burner manufacturer specifications?

6. Identify the total excess air rate for the kiln.

7. Is this excess air rate acceptable? See the preceding discussion guidelines.

8. Independently calculate the maximum total excess air rate needed to maintain the proposed operating temperature in the kiln (see Worksheet 4-8).

9. Is this calculated excess air rate greater than the proposed total excess air rate? (If YES, proceed to checkpoint #12. If NO, proceed to the following checkpoint.)

10. Is this excess air rate acceptable, even though it is less than or comparable to the proposed excess air rate? See the preceding discussion for general guidelines. (If YES, proceed to checkpoint #12. If NO, proceed to the following checkpoint.)

11. Are there any mechanical restraints in the system that would prevent increasing the auxiliary fuel-to-waste firing ratio in the kiln (which would be needed to maintain both an acceptable temperature and excess air rate). In other words, is the maximum achievable fuel-to-waste firing ratio insufficient to maintain an acceptable excess air rate? Repeat the calculations shown in Worksheet 4-8 at this fuel-to-waste ratio, if necessary.

12. Identify the total excess air rate for the system (i.e., in afterburner).

(continued)

TABLE 4-8 (continued)

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13. Is this excess air rate acceptable? See the preceding discussion for general guidelines.

14. Independently calculate the total excess air rate needed to maintain the proposed operating temperature in the afterburner (see Worksheet 4-9). Is the calculated excess air rate greater than or comparable to the proposed total excess air rate? (If YES, proceed to checkpoint #17. If NO, proceed to the following checkpoint.)

15. Is this excess air rate acceptable, even though it is less than the proposed excess air rate? See the preceding discussion for general guidelines. (If YES, proceed to checkpoint #17. If NO, proceed to the following checkpoint.)

16. Are there any mechanical restraints in the system that would prevent increasing the auxiliary fuel-to-waste firing ratio in the afterburner (which would be needed to maintain both an acceptable temperature and excess air rate)? If necessary repeat the calculations shown in Worksheet 4-9 at the maximum achievable fuel-to-waste ratio.

17. Identify the locations at which temperature is to be measured in the kiln and afterburner.

18. Are these locations (a) suitable based on the general guidelines given in the preceding discussion, or (b) comparable to the location at which temperature was measured during a prior similar burn?

This equation can be used for a rough approximation of the retention time.

Typical ranges for the parameters are L/D = 2-10, 0.03-0.09 ft/ft slope, and 1-5 ft/min rotational speed measured at the kiln periphery (which can be converted to rpm by dividing by the kiln circumference measured in ft). Some examples of retention time requirements are 0.5 s for fine propellants, 5 min for wooden boxes, 15 min for refuse, and 60 min for railroad ties [5]. However, the retention time requirements for burnout of any particular solid waste should be determined experimentally or extrapolated from operating experience with similar wastes.

Table 4-9 presents an evaluation procedure for kiln retention time.

In rotary kiln incineration systems, both the degree of air/solids contact in the kiln and gas mixing in the afterburner must be considered. Afterburner mixing considerations are essentially the same as for liquid injection incinerators, a topic which is addressed in Section 4.3.3.1. See Table 4-7 for the afterburner mixing evaluation procedure.

TABLE 4-9. KILN RETENTION TIME EVALUATION PROCEDURE

1. Identify the estimated solids retention time in the kiln.
2. Is this retention time acceptable, based on past experience and/or prior burn data?
3. Independently estimate solids retention time in the kiln (see Worksheet 4-10).
4. Does the proposed retention time appear to be achievable?

Air/solids mixing in the kiln is primarily a function of the kiln's rotational velocity, assuming a relatively constant gas flow rate. As rotational velocity is increased, the solids are carried up higher along the kiln wall and showered down through the air/combustion gas mixture. Typical rotational velocities are in the range of 1-5 ft/min, measured at the kiln periphery.

Since solids retention time is also affected by rotational velocity, there is a tradeoff between retention time and air/solids mixing. Mixing is improved to a point by increased rotational velocity, but the solids retention time is reduced. Mixing is also improved by increasing the excess air rate, but this reduces the kiln operating temperature. Thus, there is a distinct interplay between all four operating variables.

4.3.4 Auxiliary Fuel Capacity Evaluation

4.3.4.1 Liquid Injection Incinerators--

As discussed in Section 4.3.1, liquid injection incinerators should be equipped with an auxiliary fuel firing system to heat the unit to operating temperature before waste is introduced. Although not essential from an engineering standpoint, it is desirable for the auxiliary fuel system to have sufficient capacity to attain this temperature at the design air flow rate for waste combustion. This capacity requirement can be approximated by the following heat balance equation[a]:

$$0.95\ m_f\ NHV_f = m_f \sum_{i=1}^{k} n_{if}\ \overline{C_{pi}}\ (T_{out} - 77)$$

---

[a] See Section 4.3.3.1 for a discussion of how heat balances are formulated.

$$+ 4.31\ m_w\ (O_2)_{stoich(w)}\ (1 + EA)\ \overline{C_p}\ air\ (T_{out} - 77)$$

$$- 4.31\ m_f\ (O_2)_{stoich(f)}\ \overline{C_p}\ air\ (T_{out} - 77)$$

where

m_f = required auxiliary capacity, lb/hr

NHV_f = net heating value of auxiliary fuel, Btu/lb

N_{if} = lb combustion ith product lb fuel

$\overline{C_{pi}}$ = heat capacity of ith component, Btu/lb °F

T_{out} = proposed operating temperature, measured at the incinerator outlet, °F

$4.31(O_2)_{stoich(w)}$ = stoichiometric air requirement for waste combustion, lb air/lb waste

m_w = proposed waste feed rate (average), lb/hr

EA = proposed excess air rate, %/100

$4.31(O_2)_{stoich(f)}$ = stoichiometric air requirement for fuel combustion, lb air/lb fuel

This equation is based on these assumptions: (a) air is not preheated, (b) there is a 5% heat loss through the refractory walls, and (c) the air flow rate for normal waste burning operation exceeds the air requirements for fuel combustion during startup.

Since CO_2, H_2O, and N_2 are the only major components of fuel combustion gases at stoichiometric firing conditions, this equation can be further simplified using the heat capacities presented in Section 4.3.3.1 The simplified form is:

$$0.95\ m_f NHV_f = m_f\ \left[0.26\ (n_{CO_2} + n_{N_2}\ + 0.49\ n_{H_2O}\right]\ (T_{out} - 77)$$

$$+ 1.12\ m_w\ (O_2)_{stoich(w)}\ (1 + EA)\ (T_{out} - 77)$$

$$- 1.12\ m_f\ (O_2)_{stoich(f)}\ (T_{out} - 77)$$

where n_{CO_2}, n_{N_2}, n_{H_2O}, are based on the stoichiometric air/fuel ratio.

Worksheet 4-11 presents a step-by-step procedure to solve this equation for n_{1f}, the required auxiliary fuel capacity. This value can then be compared to the auxiliary fuel rating of the incinerator.

If this rating is reported in Btu/hr rather than lb/hr, the capacity requirement calculated in Worksheet 4-11 can be converted to equivalent units by:

$$Q_f = m_f \, NHV_f$$

where Q_f = required auxiliary fuel capacity, Btu/hr

4.3.4.2 Rotary Kiln Incinerators--
In rotary kiln incinerators, both the kiln and afterburner need to be heated to operating temperature before waste is introduced. Since the afterburner temperature is usually higher than the kiln temperature and more critical in terms of emissions, it should be sufficient to limit the auxiliary fuel capacity evaluation to the afterburner section. The evaluation procedure described for liquid injection incinerators can be modified for this purpose in the following manner:

- The proposed average waste feed rate (m_w) and stoichiometric air requirement for waste combustion should be based on the combined kiln and afterburner waste feed.
- Temperature (T_{out}) should be specified at the afterburner outlet.
- The excess air rate (EA) used in the calculation should be the proposed excess air level for the afterburner section.

With these modifications, Worksheet 4-11 can be used to estimate the auxiliary fuel startup requirements for rotary kiln incinerators as well as liquid injection units.

4.3.5 Combustion Process Control and Safety Shutdown System Evaluation

All incinerators should be equipped with combustion process control systems to maintain the desired conditions of temperature and excess air. Incinerators burning hazardous wastes should also be equipped with automatic shutdown systems in order to prevent the release of hazardous materials to the environment in the event of flameout, other combustion process upsets, or air pollution control device failure. The following subsections discuss combustion process control and automatic shutdown procedures related to upsets in liquid injection and rotary kiln incinerators. Process control procedures for air pollution control devices are discussed in Section 4.4.5.

4.3.5.1 Liquid Injection Incinerators--
In most liquid injection incinerator designs, the desired temperature at the chamber outlet is preset by the operator, and secondary air is fed to the system at a constant rate. Fluctuations in temperature are controlled by increasing or reducing the waste or auxiliary fuel feed rate to the burner within the design turndown ratio. This turndown ratio is fixed, in part, by the limited range of liquid waste injection velocities required to prevent flame liftoff or flashback. If waste is injected through the burner nozzle at too high a velocity, the flame will separate from the burner and be extinguished. If the injection velocity is too low, the waste will burn in the nozzle and damage it. The range of injection velocities needed to prevent

these occurrences is determined by the flame propagation rate for the wastes and the flame retention characteristics of the burner.

Since the burner turndown ratio is also limited by the atomization technique employed (see Section 4.3.1) and the need to maintain air/fuel stoichiometry in the burner on turndown, the burner must be equipped with a primary air feed control system. There are a number of ways to control burner stoichiometry, depending on whether aspirator burners or forced-draft burners are used and on manufacturer preference.[a] For evaluation purposes, a package burner/primary air control system provided by the same manufacturer can be considered sufficient.

Problems with the automatic temperature control system described above occur on loss of ignition, or flameout. When flameout occurs, the temperature in the incinerator drops and more waste is automatically fed to the burner. Without a heat source for ignition, this waste passes through the incinerator partially or completely unreacted. Thus, temperature continues to drop, more waste is automatically injected, and the problem of incomplete combustion is magnified.

To prevent this phenomenon from occurring, burners are usually equipped with flame scanners. These devices sense ultraviolet radiation from the flame. When used in conjunction with an automatic waste feed cutoff, flame scanners immediately terminate the feed to the burner on loss of ignition.

Flame scanners are usually designed to sense ultraviolet radiation from gas or fuel oil flames. These flames tend to be more stable than the flames from burning wastes which are usually much more heterogeneous than fuels. For example, organic wastes containing a significant amount of moisture burn with a sputtering flame, particularly when a slug of water passes through the burner. Although combustion may continue despite such occurrences, flame scanners often sense loss of ignition. This leads to unnecessary waste feed cutoff.

To prevent unnecessary shutdown, flame scanners can be used in conjunction with temperature sensors at the outlet of the incinerator. With this system, feed is only cut off by a combination of flameout, as sensed by the flame scanner, and low temperature at the combustion chamber. This considerably reduces operator problems when relatively heterogeneous wastes are being burned. If the low temperature cutoff is preset to the minimum temperature needed for waste destruction, release of hazardous substances to the environment is also prevented.

The other automatic shutdown parameter related to the combustion process is high temperature at the incinerator outlet. This can signal loss of secondary combustion air or other control system malfunctions. The high temperature cutoff point should be well above the tolerance level associated with normal operating temperature fluctuations to prevent shutdown in the event of routine variations, and should be low enough to prevent damage to downstream air pollution control equipment.

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[a] In aspirator burners, primary air is supplied by an induced-draft fan downstream from the incinerator. In forced-draft burners, primary air is supplied by a separate blower, although an induced-draft fan may still be employed to pull the combustion gases through the air pollution control system.

Table 4-10 lists three checkpoints for liquid injection incinerator combustion process control evaluation.

4.3.5.2 Rotary Kiln Incinerators--
In rotary kiln incinerators, temperature is controlled within a specified range by automatically varying the liquid waste or auxiliary fuel firing rate within the design turndown ratio and/or manually or automatically controlling the solid waste feed. Regardless of which technique is employed, provisions should be included for the following:

- Termination of liquid waste feed on loss of ignition in the burner. If more than one liquid waste burner is employed, feed only needs to be terminated in the burner where flameout occurs. See Section 4.3.5.1 for a discussion of flame supervision systems.
- Termination of solid waste feed to the kiln when low temperatures are sensed at the kiln outlet. If the feed to the kiln is automatic or semiautomatic, then the low temperature cutoff system should also be automatic. If manual feeding is employed, an alarm system is needed to warn the operator. The low temperature cutoff point should be such that solid waste burnout can be maintained, but at lower than the normal operating temperature to avoid shutdown due to routine temperature fluctuations. Engineering judgment must be used to determine an acceptable minimum temperature.
- Termination of solid waste feed on loss of negative pressure at the kiln outlet.

TABLE 4-10. COMBUSTION PROCESS CONTROL EVALUATION PROCEDURE

1. Is each burner equipped with an automatic flame supervision system, as discussed in the preceding subsection, (Section 4.3.5.1)?

2. Is the system equipped with an automatic high temperature/low temperature control system, employing variable flow of either waste or auxiliary fuel?

3. Is each burner equipped with an air supply control system so that air: fuel stoichiometry is maintained on turndown?

Afterburner burner temperature can be controlled by varying the liquid or auxiliary fuel feed or by varying the secondary air flow rate. Regardless of which technique is employed, provisions should be included for the following:

- Termination of liquid waste or auxiliary fuel feed on loss of ignition (see Section 4.3.5.1 for a discussion of flame supervision). This cutoff is necessary to prevent the release of unburned waste contaminants (if liquid waste is being burned) and to prevent potential explosion on release of unburned fuel. However, it also eliminates the function of the afterburner. Therefore, solid waste feed to the kiln should also be terminated on loss of ignition in the afterburner. To minimize the occurrence of flameout in the afterburner, only "clean," homogeneous liquid wastes (or fuel) should be burned.

- Termination of solid waste feed to the kiln if low temperatures are sensed at the afterburner outlet. The afterburner feed should be maintained, however, to minimize potential release of unburned contaminants. As previously stated, the low temperature cutoff point should be such that combustion is maintained, but at lower than normal operating temperatures to avoid shutdown due to routine fluctuations.

- Termination of solid waste feed to the kiln if high temperatures are sensed at the afterburner outlet. This is necessary to prevent damage to the refractory lining and to downstream air pollution control devices. The high temperature cutoff point should be well above normal operating temperatures, but low enough to avoid damage to the system. In the event of this cutoff, some liquid waste or fuel feed to the afterburner should be maintained to complete combustion of off-gases from solid wastes remaining in the kiln.

In addition to these criteria, all liquid waste burners in the kiln and afterburner should be equipped with manufacturer specified primary air control systems so that air/fuel stoichiometry is maintained on turndown.

Table 4-11 presents a five-point checklist for rotary kiln incinerator combustion process control evaluation.

TABLE 4-11. COMBUSTION PROCESS CONTROL EVALUATION PROCEDURE

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1. Is each burner in the kiln and afterburner equipped with an automatic flame supervision system for waste feed shutdown?

2. Is the afterburner equipped with an automatic high temperature/low temperature control system employing variable flow of waste, auxiliary fuel, or secondary combustion air?

3. Is the kiln equipped with an automatic temperature control system employing variable feed of either waste or auxiliary fuel?

(continued)

TABLE 4-11 (continued)

4. Is the kiln equipped with a pressure monitoring system which alerts the operator or automatically terminates waste feed if negative pressure is lost?

5. Is each burner equipped with an air supply control system so that air:fuel stoichiometry is maintained on turndown?

4.3.6 Construction Material Evaluation

Since hazardous waste incinerators usually operate at temperatures of 1,800°F or higher (sometimes hundreds of degrees higher for halogenated wastes), refractory linings are virtually always employed to prevent damage to the structural steel shell and to reduce heat loss. Aluminosilicate refractories backed up by insulating brick are most commonly used, although refractories made predominantly of silica or specialty refractories may be used in certain applications. Table 4-12 lists various types of aluminosilicate and silica refractories[a] along with their approximate chemical compositions, fusion temperatures, and resistances to degradation by different chemical species that may be encountered in incinerator combustion gases.

Table 4-12, along with the operating temperature range and the chemical composition of the waste, can be used to evaluate the suitability of a refractory for a given application.

In addition to refractory composition, the physical form of the material should also be considered in evaluating liquid injection vs. rotary kiln incinerator designs. Suspended refractory brick is normally used in stationary liquid injection units and afterburners. In kilns, however, castable refractories are normally used to better withstand the physical abrasion and vibration imparted by rotation and contact with solid wastes. Castable refractories are made of the same clays as those used in aluminosilicate firebrick, but bonding agents are added to impart strength until the temperature in the incinerator during initial startup is raised sufficiently high to "cure" the material and develop ceramic bonds. Castable refractories are easily installed in much the same manner as cement; thus, they are also used for quick repairs and spot patching.

4.4 AIR POLLUTION CONTROL AND GAS HANDLING SYSTEM DESIGN EVALUATION

Figure 4-11 presents a logic diagram for air pollution control and gas handling system design evaluation. It consists of six separate evaluation procedures intended to answer the following questions:

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[a] See references listed in Table 4-12 for information on specialty refractions.

TABLE 4-12. GENERAL CHARACTERISTICS OF SILICA AND ALUMINO-SILICATE REFRACTORY BRICK [6, 7, 8, 9, 10]

Type	Typical composition	Fusion temperature, °F[a]	Resistant to	Degraded by
Silica	95% SiO_2	3,100	HCl, NH_3, acid slags	Basic slags, Al, Na, Mg, F_2, Cl_2, H_2, (>2,550°F)
High-duty fireclay	54% SiO_2, 40% Al_2O_3	3,125	Most acids, slag conditions	High-lime slags, other bases at high temperature
Super-duty fireclay	52% SiO_2, 42% Al_2O_3	3,170	HCl, NH_3, SO_2, most acids	Basic slags, Na, Mg, F_2, Cl_2, H_2, (>2,550°F)
Acid-resistant (type H)	59% SiO_2	3,040	Excellent for most acids; bases in moderate concentration	HF, H_3PO_4
High-Alumina	50-85% Al_2O_3	3,200-3,400	HCl, NH_3, SO_2	Basic slags, Na, Mg, F_2, Cl_2, H_2 (>2,550°F)
Extra-High-Alumina	90-99% Al_2O_3	3,000-3,650	HCl, HF, NH_3, SO_2, S_2, HNO_3, H_2SO_4, Cl_2	Na, F_2 (>1,800°F)
Mullite	71% Al_2O_3	3,290	HCl, SO_2, NH_3	Na, F_2, Cl_2, H_2 (>2,550°F)

[a] A safety factor of at least several hundred degrees between refractory fusion temperature and incinerator operating temperature is advisable.

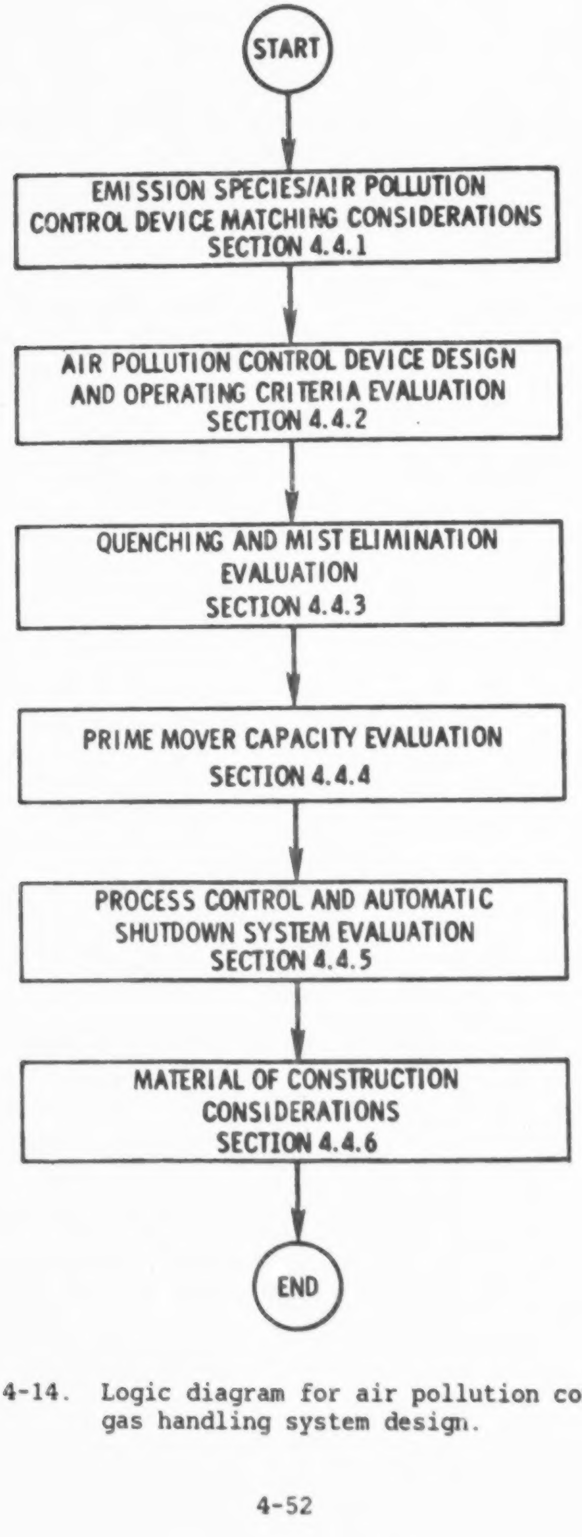
START
EMISSION SPECIES/AIR POLLUTION CONTROL DEVICE MATCHING CONSIDERATIONS SECTION 4.4.1
AIR POLLUTION CONTROL DEVICE DESIGN AND OPERATING CRITERIA EVALUATION SECTION 4.4.2
QUENCHING AND MIST ELIMINATION EVALUATION SECTION 4.4.3
PRIME MOVER CAPACITY EVALUATION SECTION 4.4.4
PROCESS CONTROL AND AUTOMATIC SHUTDOWN SYSTEM EVALUATION SECTION 4.4.5
MATERIAL OF CONSTRUCTION CONSIDERATIONS SECTION 4.4.6
END

Figure 4-14. Logic diagram for air pollution control and gas handling system design.

(1) Are the generic air pollution control device designs appropriate for removal of the pollutants present in the combustion gases?

(2) Are the air pollution control device designs and operating criteria consistent with current industry practice and capable of achieving the necessary pollutant removal efficiencies?

(3) Have combustion gas quenching and mist elimination been properly considered in the system design?

(4) Does the prime mover have sufficient capacity to handle the combustion gas flow and overcome pressure drops across the air pollution control system?

(5) Are appropriate process control and safety shutdown interlocks incorporated?

(6) Are appropriate materials of construction employed?

These topics are addressed in Sections 4.4.1 through 4.4.6

4.4.1 Emission/Air Pollution Control Device Matching Criteria

When incinerating hazardous wastes, air pollutants may arise from two sources: incomplete combustion of organic waste constituents and conversion of certain inorganic constituents present in the waste and/or combustion air to ultimate oxidation products. The products of incomplete combustion include carbon monoxide, carbon, hydrocarbons, aldehydes, amines, organic acids, polycyclic organic matter (POM), and any other waste constituents or their partially degraded products that escape thermal destruction in the incinerator. In well designed and operated incinerators, however, these incomplete combustion products are only emitted in insignificant amounts. The primary end products of combustion are, in most cases, carbon dioxide (CO_2) and water vapor (H_2O).

When wastes containing elements other than carbon, hydrogen, and oxygen are burned, however, ultimate combustion products other than CO_2 and water vapor are formed. These include:

- Hydrogen chloride (HCl) and small amounts of chlorine (Cl_2) from the incineration of chlorinated hydrocarbons,
- Hydrogen fluoride (HF) from the incineration of organic fluorides,
- Bromine (Br_2) and lesser quantities of hydrogen bromide (HBr) when organic bromides are burned,
- Iodine (I_2) from organic iodide compound incineration,
- Sulfur oxides, mostly as sulfur dioxide (SO_2), but also including 1% to 5% sulfur trioxide (SO_3), formed from sulfur present in the waste material and auxiliary fuel,

- Phosphorus pentoxide (P_2O_5), formed from the incineration of organophosphorus compounds,

- Nitrogen oxides (NO_x) from thermal fixation of nitrogen in the combustion air or from organic nitrogen compounds present in the waste, and

- Particulates, including metal salts from the waste, metal oxides formed by combustion, and fragments of incompletely burned material (primarily carbon).

Gaseous pollutant concentrations in the combustion gases leaving an incinerator can be estimated by the methods described in Section 4.3.2[a]. Step-by-step procedures for calculating these concentrations are presented in Worksheets 4-2 and 4-4. Particulate emissions from liquid injection incinerators can also be estimated from the ash content of the waste, the combustion gas flow rate corrected to standard conditions of temperature and pressure (see Worksheets 4-2 and 4-12), and the oxygen content of the combustion gas. Oxygen concentration is important because particulate loadings are often expressed as gr/scf (mg/m^3) corrected to zero percent excess air. A procedure to estimate particulate concentrations in combustion gases from liquid injection incinerators is presented in Worksheet 4-12. Particulate emissions from rotary kilns are more difficult to estimate because sizable fractions of incombustible material are removed as bottom ash, and the fly ash:bottom ash ratio is usually unknown prior to actual testing. In general, particulate emissions from rotary kilns burning solid wastes are greater than particulate emissions from liquid injection incinerators. This is due to the fact that solid wastes frequently have a higher ash content than liquid wastes.

As indicated in Section 4.1, venturi scrubbers, packed bed scrubbers, and plate tower scrubbers are used for air pollution control at the majority of hazardous waste incineration facilities. In selecting from among these generic scrubber designs, the factors most frequently considered are the need for particulate emission control, particulate loading in the combustion gas (assuming that control is required to meet emission standards), the types of gaseous pollutants to be removed, and the desired removal efficiencies. Particulate loading governs the choice between venturi and packed bed or plate tower scrubbers for a given application, and the characteristics of the gaseous emission species govern the choice of scrubber medium (e.g., water vs. caustic solution, lime solution, etc.) as well as generic scrubber design.

These factors are discussed in the following subsections.

4.4.1.1 Particulate Removal--

Particulate removal is required when the ash content of the waste is such that emissions will exceed applicable state, local, or Federal standards. Particulate removal is nearly always required at rotary kiln incineration facilities, and may or may not be required for liquid injection incinerators depending on the ash content of the waste. (See Worksheet 4-12 for a method to estimate particulate emissions from liquid incinerators.) Venturi, packed bed, and plate tower scrubbers can all be used to control particulate emissions from hazardous waste incinerators, depending on the particulate loading in the gas. Packed bed or plate tower scrubbers are commonly used at liquid injection incinerator facilities where particulate control is considered secondary to gaseous emission control. These devices are superior to venturi scrubbers for removal of gaseous pollutants and they operate at lower pressure drops; thus they are more economical to operate. Both the plate tower and the packed bed scrubber have some capacity for particle collection, and they are considered applicable for streams containing low particulate loadings with particles generally >5 µm in diameter [11]. Cut diameters as low as 1 µm can be attained with plate scrubbers or packed bed scrubbers employing 1-inch berl saddles or Raschig rings [12]. However, packed bed and plate tower scrubbers are not primarily designed for particulate control. Both devices, particularly packed bed scrubbers, are susceptible to pluggage by solids. Therefore, they are seldom, if ever, used as the primary particulate collection devices at rotary kiln incineration facilities or liquid injecton incineration facilities where high ash content wastes are burned. Venturi scrubbers are the most popular devices for these applications.

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[a] These procedures are not applicable for products of incomplete combustion.

High energy venturi scrubbers are capable of 99% removal of particulate in the 1- to 2-µm size range and above, 90-99% removal of particulate in the 0.5 - to 1-µm size range, and 50% removal of particulate in the 0.3- to 0.5-µm size range [13]. By comparison, particulates emitted from liquid and solid waste incinerators have mean diameters in the 0.5- to 3-µm and 5- to 100-µm ranges, respectively. Therefore, venturi scrubbers are capable of efficient particulate removal for most hazardous waste incineration applications.

Table 4-13 presents a checklist procedure that can be used to compare particulate removal requirements with proposed control strategies.

TABLE 4-13. PROCEDURE TO COMPARE PARTICULATE REMOVAL REQUIREMENTS WITH PROPOSED CONTROL STRATEGIES

1. If a rotary kiln incinerator facility is being evaluated, is a venturi scrubber provided for particulate control?

2. If a liquid injection incinerator facility is being evaluated, does the estimated particulate emission rate exceed applicable standards? See Worksheet 4-12 for a procedure to estimate particulate emissions.

3. If particulate emissions do exceed standards, is a venturi scrubber provided for particulate removal (upstream from other gaseous emission control devices)?

4. If not, are packed bed or plate tower scrubbers to be used for simultaneous particulate and gaseous pollutant removal?

5. If so, can the selected control device function properly in its dual role? (Technical assistance may be needed to make this determination).

4.4.1.2 Gaseous Pollutant Removal--
Gaseous pollutants generated by hazardous waste incineration include HCl, Cl_2, SO_x, Br_2, HBr, HF, P_2O_5 and NO_x, of which NO_x and HCl are most commonly encountered.[a,b,c] These compounds are usually removed from the combustion gases by packed bed or plate tower scrubbers, although venturi scrubbers are used in some applications for simultaneous particulate and gaseous pollutant removal. For highly soluble gases such as HCl and HF, water can be used in packed bed or plate tower scrubbers to control emissions. When water is used as the scrubbing liquor, an acidic blowdown stream is produced that must be neutralized prior to discharge. HCl concentration in the scrubbing liquor is normally limited to 1-2% by adjusting the makeup water and blowdown rates. The scrubber must also be lined with an acid-resistant material, as discussed in Section 4.4.6.

Caustic solution (typically 18-20 wt % caustic soda in water) is also commonly used in packed bed and plate tower scrubbers to control HCl and HF emissions. Because these compounds react with caustic, the driving force for mass transfer is increased and more efficient removal is achieved at the same liquid-to-gas ratio and packing depth (or number of trays). Neutralization is also achieved "in situ" if sufficient caustic is supplied for complete conversion of HCl to NaCl. Unlike water scrubbing, caustic scrubbing can also achieve high removal efficiencies for SO_2, P_2O_5, and HBr, which are less soluble in water than HCl or HF. When gases such as SO_2 are being scrubbed, the caustic addition rate is adjusted to maintain an alkaline scrubbing media. Alternatively, the caustic addition rate can be adjusted to sub-stoichiometric levels. This reduces the scrubber water makeup and blowdown rates needed to maintain a specified acid concentration in the scrubber liquor.

Lime slurry, typically 10-32 wt % $Ca(OH)_2$ in water, can also be used to control emissions of HCl, HF, SO_2, and P_2O_5. However, lime slurries are not often used as the scrubbing liquid in packed bed designs because of plugging problems. Also, the use of lime slurries can lead to plugging of the spray nozzles and cause scale formation on the surfaces of the scrubber equipment, particularly scrubber internals and mist eliminator surfaces. The magnitude of the scaling problem will depend on the levels of HCl, HF, P_2O_5, and SO_x in the incinerator exhaust gases. Lime solutions are used in plate tower scrubbers, however, because lime is less expensive than caustic. At several hazardous waste incineration facilities, venturi scrubbers with lime slurry injection are used to control emissions of HCl, HF, and P_2O_5.

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[a] NO_x emissions are not economically amenable to control by scrubbing or other post-generation removal techniques. NO_x emissions can be minimized by controlled temperature combustion, but this is seldom possible in hazardous waste incineration due to the requirements for efficient, high temperature waste destruction.

[b] I_2 and HI emissions may be an occasional problem as well.

[c] Cl_2 is present in conjuncton with HCl, but equilibrium favors HCl formation at the high temperatures employed in chlorinated waste incinerators. Cl_2 and the other free halogens are not readily removed by scrubbing.

When organic bromine and iodine wastes are incinerated, the exhaust gases from the incinerator will contain bromine and iodine both as hydrogen halides and as free halogens. Hydrogen bromide can be readily removed by scrubbing with caustic soda. The technology for controlling emissions of bromine, hydrogen iodide, and iodine, however, is not well developed. Some of the methods that could be considered to control bromine emissions include: (1) absorption in ammonia solution with the formation of ammonia bromide; (2) absorption in caustic soda or soda ash solution in which bromine reacts to form sodium bromate, sodium bromide, and either water or carbon dioxide; and (3) absorption in lime slurry in which bromine reacts to form calcium bromide and calcium bromate. It is also conceivable that bromine can be reduced by the sulfur dioxide present in the flue gas, giving rise to the formation of a spray of fine droplets of hydrobromic and sulfuric acids, which could subsequently be removed by absorption in caustic solutions or lime slurries.

When combustion gases contain a high particulate loading as well as one or more of the gaseous pollutants discussed above, venturi scrubbers are often used in conjunction with packed bed or plate tower scrubbers. Venturi scrubbers remove the particulate from the stream to prevent fouling of the packed bed or plate tower absorber, and may also remove a significant fraction of gases highly soluble in water. However, venturi scrubbers alone are not considered suitable for removal of low solubility gases; when water is used as the scrubbing medium, estimated efficiencies are less than 50-75% [11]. Venturi scrubbers using water are not suitable for highly efficient (>99%) removal of HCl or HF either.

Table 4-14 presents a checklist procedure that can be used to compare gaseous pollutant removal requirements with proposed control strategies. The following rules of thumb are generally applicable:

- Water, caustic, or lime in packed bed or plate tower scrubbers for removal of HCl and/or HF,
- Caustic or lime in packed bed or plate tower scrubbers for removal of other acid gases discussed above, and
- Specialized scrubbing techniques for HBr, Br_2, HI, and I_2. Technical assistance is advised in evaluating these systems.

4.4.2 Air Pollution Control Device Design and Operating Criteria Evaluation

4.4.2.1 Venturi Scrubbers--

Venturi scrubbers utilize the kinetic energy of a moving gas stream to atomize the scrubbing liquid into droplets. Liquid is injected into the high velocity gas stream either at the inlet to the converging section or at the venturi throat. In the process, the liquid is atomized by the formation and subsequent shattering of attenuated, twisted filaments and thin, cuplike films. These initial filaments and films have extremely large surface areas available for mass transfer [14].

Venturi scrubbers are usually designed for particulate collection, but they can be used for simultaneous gas absorption as well. However, the design of

TABLE 4-14. PROCEDURE TO COMPARE GASEOUS POLLUTANT REMOVAL REQUIREMENTS WITH PROPOSED CONTROL STRATEGIES

1. From Worksheet 4-2 or 4-4, identify the gaseous pollutants present in the combustion gases in excess of desired emission levels.
2. Is removal of Br_2, HBr, I_2, or HI required? If YES, technical assistance may be required.
3. Is removal of SO_x or P_2O_5 required? If YES, proceed to checkpoint #4. If NO, proceed to checkpoint #5.
4. Is caustic or lime slurry scrubbing to be used for SO_x/P_2O_5 removal, as described in the preceding pages? (Water scrubbing alone is usually not sufficient to remove these compounds).
5. Is removal of HCl or HF required?
6. Is alkali or aqueous scrubbing in a packed bed or plate tower scrubber, or alkali scrubbing in a venturi scrubber, to be used for HCl/HF removal?
7. If not, are other methods for HCl/HF removal provided?
8. If so, are these methods acceptable? (Technical assistance may be needed to make this determination).

venturi scrubbers for removal of gaseous contaminants is dependent on the availability of applicable experimental data. There is no satisfactory generalized design correlation for these types of scrubbers, especially when absorption with chemical reaction is involved. Reliable design must be based on full-scale data or at least laboratory- or pilot-scale data.

Correlations are available to design venturi scrubbers for particulate removal. The important design parameters are particulate loading and desired removal efficiency, particle size distribution, pressure drop, liquid-to-gas ratio, and gas velocity.

Particulate loading, size distribution, and removal efficiency--If the particulate size distribution and desired removal efficiency are known, several correlations can be used to predict the required cut diameter for design purposes. Calvert et al. [15] have developed parametric plots of overall penetration versus the ratio of cut diameter to mass median diameter with geometric standard deviation as the third parameter. These plots can be used to determine the required cut diameter if the desired removal efficiency and particle size distribution are known. Cut diameter can then be related to pressure drop, liquid-to-gas ratio, and gas velocity for design purposes as described in the following subsection.

Hesketh [16] has also developed an empirical relationship between penetration of all particles 5 µm or less in diameter and the pressure drop across venturis based on data from the collection of a variety of industrial dusts. Assuming that particles larger than 5 µm are collected with 100% efficiency, this relationship may be utilized with size distribution data to estimate overall penetration:

$$Pt = 0.065W(\Delta P)^{-1.43}$$

where Pt = fractional penetration
W = the weight fraction of inlet particles 5 µm or less in diameter
ΔP = pressure drop, in. WG

The major drawback in applying these correlations to venturi scrubber design evaluation is that the particle size distribution will rarely be known until testing is performed after startup. The size distribution of particles emitted from an incinerator depends upon the relative number of particles generated by several factors responsible for the formation of particulate emissions: (1) mechanical entrainment of combustible and noncombustible particles in the furnace gases, (2) pyrolysis of hydrocarbons and subsequent condensation, and (3) volatilization of metallic salts and oxides present in the wastes and auxiliary fuels. Further, particle growth due to agglomeration and condensation of moisture between the incinerator and the control device will affect the particle size distribution. There is no method for the *a priori* prediction of particle size distributions resulting from waste incineration. While incineration of liquid wastes may result in mean particle diameters in the 0.5- to 3-µm range, mean particle diameters resulting from incineration of solid waste could range from 5 to 100 µm, depending upon the size distribution of feed solids, their combustion characteristics, and the incinerator design. If particle size distribution data is available, methods described in references 15 or 16 can be used to determine the required cut diameter.

Pressure drop, liquid-to-gas ratio, and gas velocity--As described above, particle cut diameter is a frequently used parameter for expressing and determining the particle collection performance of wet scrubbers. One reason for this is because plots of collection efficiency versus particle diameter tend to be rather steep in the region where inertial impaction is the predominant collection mechanism. Because the cut is fairly sharp for venturi scrubbers, a rough approximation of scrubber performance may be made by assuming that particles larger than the cut diameter are collected with 100% efficiency while those smaller will not be collected. A plot of cut diameter versus pressure drop for gas-atomized scrubbers is presented in Figure 4-15 [12]. The plot is based on industrial and experimental data as well as mathematical models, and can be used in conjunction with the methods developed by Calvert et al. [15] to estimate penetration as a function of pressure drop.

Available data indicate that venturis at hazardous waste incineration facilities operate with pressure drops in the 30- to 50-in. WG range. Based on Figure 4-15, this indicates that venturi scrubbers at these facilities are designed for 0.3- to 0.4-µm cut diameters.

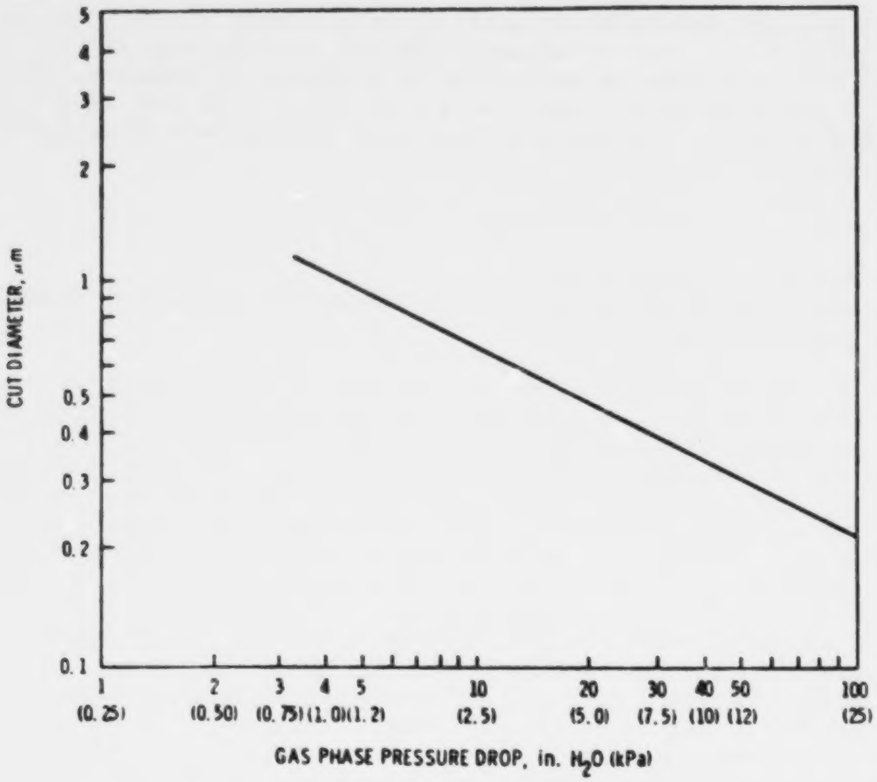

Figure 4-15. Pressure drop versus cut diameter for gas-atomized scrubber systems (Experimental data from large venturis, other gas-atomizers, scrubbers, and mathematical model.) [12].

Pressure drop in venturi scrubbers is theoretically related to gas velocity and liquid-to-gas ratio, as shown in the following relation developed by Calvert [15]. This relationship assumes that all energy is used to accelerate the liquid droplets to the throat velocity of the gas.

$$\Delta P = 2.12 \times 10^{-5}(U_G)^2 \frac{Q_L}{Q_G}$$

where ΔP = pressure drop, in. WG

U_G = gas velocity, ft/s

Q_L/Q_G = liquid-to-gas ratio, gal/1,000 ft^3

An alternative empirical approach by Hesketh [16] indicates that the pressure drop for venturis is proportional to $U_G{}^2$ and $(Q_L/Q_G)^{0.78}$, as well as to the gas density ρ_G (measured downstream from the venturi throat) and to $A^{0.133}$, where A is the cross-sectional area of the venturi throat:

$$\Delta P = \frac{(U_G)^2 \rho_G A^{0.133} \left(\frac{Q_L}{Q_G}\right)^{0.78}}{1270}$$

Pressure drop will be relatively unsensitive to changes in A because of the small exponent, but density will be inversely proportional to the gas temperature. These relationships can be used as internal consistency checks for the proposed conditions of gas velocity, liquid-to-gas ratio, and pressure drop.

Liquid-to-gas ratios for venturi scrubbers are usually in the range of 5 to 20 gal/1,000 ft^3 of gas. At existing hazardous waste incineration facilities, liquid-to-gas ratios ranging from 7 to 45 gal/1,000 ft^3 of gas have been reported. In many cases, a minimum ratio of 7.5 gal/1,000 ft^3 is needed to ensure that adequate liquid is supplied to provide good gas sweeping. Gas velocity data are not available at this time for venturi scrubbers operating at hazardous waste incineration facilities. Typical venturi throat velocities for other applications, however, are in the 100- to 400-ft/s range. The low end of this range, 100-150 ft/s, is typical of power plant applications, while the upper end of the range has been applied to lime kilns and blast furnaces.

Table 4-15 presents a procedure that can be used to evaluate proposed design and operating criteria for venturi scrubbers.

TABLE 4-15. VENTURI SCRUBBER DESIGN EVALUATION PROCEDURE

1. Is the design pressure drop comparable to current industry practice (i.e., 30-50 in. WG)?
2. Are the proposed gas velocity and liquid-to-gas ratio comparable to current industry practice?
3. Are the design pressure drop, gas velocity, and liquid-to-gas ratio internally consistent? (see Worksheet 4-13.)

4.4.2.2 Packed Bed Scrubbers--

As described in Chapter 2, packed bed scrubbers are vessels filled with randomly oriented packing material such as saddles and rings. The scrubbing liquid is fed to the top of the vessel, with the gas flowing in either cocurrent, countercurrent, or crossflow modes. As the liquid flows through the bed, it wets the packing material and thus provides interfacial surface area for mass transfer with the gas phase. Water and caustic solution are both commonly used as the liquid absorbent.

In the absorption of gaseous contaminants, the rate of mass transfer is directly proportional to the concentration gradient driving force, and restricted by both gas and liquid film resistances. The primary design variables for gas absorption are the depth of packing, liquid-to-gas ratio, superficial gas velocity, and contact time. Pressure drop across the bed is also an important design consideration, but does not directly affect absorption efficiency. Packed bed scrubbers can be used for limited particulate collection as well as gas absorption, but, as explained in Section 4.4.1, they are not primarily designed for this purpose.

Packing depth--The depth of packing required is best calculated from the following expression [6]:

$$Z = N_{OG} \times H_{OG}$$

where Z is the packing depth, N_{OG} is the number of overall transfer units, and H_{OG} is the height of a transfer unit.

The number of transfer units depends on the removal efficiency requirement. In gaseous emission control for hazardous waste incineration, the gaseous contaminants to be removed usually constitute less than 10% of the total gas stream because of the presence of nitrogen, oxygen, carbon dioxide, and water vapor as the major gaseous components. Under these circumstances, the number of transfer units can be calculated from the expression [6]:

$$N_{OG} = \int_{Y_2}^{Y_1} \frac{dY}{Y - Y_e}$$

where Y is the actual gas concentration of the contaminant, Y_2 is the concentration at the scrubber outlet, Y_1 is the concentration at the inlet, and Y_e is the gas concentration of the contaminant in equilibrium with the scrubbing liquid. In industrial applications, the gaseous contaminant is often very soluble in the scrubbing liquid, as is the case of hydrogen chloride in water, or reacts very rapidly with the scrubbing liquid, as is the case of hydrogen chloride with caustic solution. For both of these cases, the equilibrium gas concentration is negligible and the number of transfer units can be calculated as:

$$N_{OG} = \ln\left(\frac{Y_1}{Y_2}\right)$$

where Y_1 and Y_2 are the inlet and outlet concentrations of the gaseous contaminant.

The height of a transfer unit is a characteristic of the particular system, and is influenced by the type and size of packing, gas and liquid flow rates, and gas and liquid physical and chemical properties. It is often taken as a constant over fixed ranges of operation and is given by the expression [6]:

$$H_{OG} = \frac{G}{K_g aP}$$

where G is the total gas flow rate per unit cross section of bed, K_g is the overall gas mass transfer coefficient, a is the interfacial surface area per unit volume of packing, and P is the total pressure. Values of $K_g a$ for many of the more commonly used gas absorption processes have been published in the literature [17,18]. Typical values of $K_g a$ are given in Table 4-16. For gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, the height of a transfer unit H_{OG} is typically in the 1 to 1.7-ft range.

TABLE 4-16. TYPICAL VALUES OF $K_g a$ [18]

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Gas	Scrubbing solution	$\frac{\text{lb mole}}{\text{in. } H_2O \cdot ft^3 \cdot s}$
Cl_2	NaOH	1.4×10^{-5}
HCl	H_2O	1.1×10^{-5}
SO_2	NaOH	4.8×10^{-6}
CO_2	NaOH	1.6×10^{-6}
SO_2	H_2O	2.2×10^{-7}
Cl_2	H_2O	9.5×10^{-8}

The transfer unit concept can be used to calculate packing depth requirements if overall gas mass transfer coefficients are available. For quicker estimates, however, other methods can be used. In Table 4-17, the estimated depths of packing beds required are given for various removal efficiencies of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid. These estimated packing depth requirements are based on the general rule that 1 in. size packings yield an H_{OG} (height of a transfer unit) equal to 1 ft, 1-1/2 in. size packings yield an H_{OG} equal to 1.3 ft, and 2 in. size packings yield an H_{OG} equal to 1.5 ft [11].

The depth of packed beds for gaseous emission control typically ranges from 4.0 to 9.3 ft. The depth of packing can also be changed if removal efficiency is lower than anticipated or if the carrier gas flow rate or waste streams incinerated change. However, an evaluation of the packing depth requirement is still desirable to assure that a packed tower design has sufficient capacity.

Liquid-to-gas ratio--The liquid-to-gas ratio is a design and operating parameter of prime importance. It is needed in the determination of the scrubber diameter, and it has an effect on the height of a transfer unit. A high liquid-to-gas ratio will lead to the requirement of a larger diameter, but at the same time will also reduce the height of a transfer unit.

TABLE 4-17. PACKING DEPTH REQUIRED TO ACHIEVE SPECIFIED REMOVAL EFFICIENCY[a] [11]

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Removal efficiency, percent	Packing size				
	1 in.	1-1/2 in.	2 in.	3 in.	3.5 in.
	Depth, ft				
90	2.5	3.2	3.74	5.74	6.99
95	3.0	3.74	4.49	6.76	8.50
98	4.00	4.99	6.00	8.99	11.3
99	4.59	5.74	6.99	10.2	13.0
99.5	5.24	6.50	8.01	12.0	14.8
99.9	6.99	8.76	10.5	15.7	19.8
99.99	9.25	11.5	14.0	21.0	26.0

[a] Applicable only to gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid. Also, there are variations in packing depths vs. the type of packing used (approximately ±25% to 30%) which have not been taken into account.

For each set of design conditions, there is a minimum liquid-to-gas ratio that is required to achieve the desired removal efficiency. This minimum ratio can be computed from equilibrium relationships. For gas contaminants that are highly soluble or chemically reactive with the scrubbing liquid, the equilibrium vapor pressure approaches zero. Theoretically, there is no minimum liquid-to-gas ratio for the removal of these gas contaminants, based on vapor-liquid equilibrium considerations. In practice, of course, sufficient scrubbing liquid must be provided to assure that it is not saturated with the gas contaminants removed, and to keep the packing surfaces thoroughly wet. When scrubbing HCl, for example, acid concentration in the scrubber liquor is normally limited to 1-2%.

The chemical requirement for acid gas neutralization in a scrubber is directly proportional to the halogen content, sulfur content, and phosphorus content of the hazardous waste streams incinerated. If caustic soda is used, at 60%[a] in excess of the stoichiometric amount, the requirement is given as:

Caustic soda requirement (lb/lb waste) = 0.0176 x wt % Cl in waste + 0.0328 x wt % F in waste + 0.0604 x wt % P in waste + 0.0389 x wt % S in waste

If the caustic content of the scrubbing solution is known, the minimum liquid flow rate for neutralization can then be calculated in terms of gallons of solution per pound of waste incinerated. The combustion gas yield per pound of waste (previously calculated in Section 4.3.2) can then be used in conjunction with this value to determine the minimum liquid-to-gas ratio in units of gallons per standard cubic foot of combustion gas.

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[a] 60% excess is typical for single pass scrubbing. When scrubber liquid is recycled, 5-30% excess can be acceptable for neutralization.

Such methods can be used to determine the chemical requirements and minimum liquid-to-gas ratio for scrubber water neutralization. However, complete neutralization is not required for efficient acid gas scrubbing, as evidenced by the fact that water is often used as the scrubbing liquor. When water is used, acid gas solubilities as functions of temperature must be known to accurately determine equilibrium relationships and minimum liquid-to-gas ratios. A more complex situation is encountered in caustic scrubbing since absorption in water and reaction occur simultaneously.

A simpler approach to evaluating minimum liquid-to-gas ratio requirements is to examine current industry practices and/or to rely on actual test data. Normal liquid-to-gas ratios in packed beds vary from 6 to 75 gal/1000 acf, with most units operating at between 22 and 52 gal/1000 acf. In general, lower liquid-to-gas ratios are needed for once-through scrubbing systems than for recycle systems to achieve the same removal efficiency because the driving force for mass transfer is greater for once-through scrubbing. Likewise, increasing the caustic addition rate will lower the minimum required liquid-to-gas ratio, all other factors being equal.

The upper limit for liquid-to-gas ratio in packed towers is set by the flooding condition. Generalized correlations of flooding velocities are available and can be used to estimate the maximum liquid-to-gas ratio [6]. In practice, however, flooding can be readily detected by sharply increased pressure drop across the packed bed, and it can be eliminated by adjustment of the liquid flow rate during operation. A quick check for proper column diameter sizing can be accomplished by calculating the superficial gas velocity through the tower. For packed beds with countercurrent flow, superficial gas velocities are normally in the range of 7 to 10 ft/s, corresponding to approximately 60% of the flooding velocity. The 40% safety factor allows for fluctuating gas flows from the incinerator caused by changing waste composition and feed rate.

Contact time--In gas absorption devices, higher efficiencies are attained by allowing the gas and liquid phases to be in contact for a longer period of time. Removal efficiencies for gaseous contaminants in packed beds are directly related to the depth of packing, which in turn determines the contact time.

The contact time required for gas absorption is a function of the rate of mass transfer. The mass transfer rate, in general, is dependent upon four separate resistances: gas phase resistance, liquid phase resistance, chemical reaction resistance, and a solids dissolution resistance for scrubbing liquids containing solid reactants. For absorption of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, such as the absorption of HCl by caustic solution, the contact time required for 99% removal is extremely short (on the order of 0.4 to 0.6 s).

Pressure drop--For gas flow through packed beds, the pressure drop may be calculated using the approximate correlation developed by Leva [6]:

$$\Delta P/Z = C_2 \, 10^{C_3 U_L} \rho_G U_G^2$$

where $\Delta P/Z$ is the pressure drop in in. WG/ft of packing, U_L is the liquid superficial velocity in ft/s, ρ_G is the gas density in lb/ft^3, U_G is the superficial gas velocity in ft/s, and C_2 and C_3 are constants. Pressure drops for the common commercial packings can also be obtained from plots of pressure drop versus gas and liquid flow rates. These plots are available from the packing manufacturers and should be used for more accurate estimation of pressure drop in the design evaluation process. For packed beds used for gaseous emission control in hazardous waste incineration facilities, the pressure drop usually ranges from 2.0 to 7.2 in. WG. Since the total pressure drop across the packed bed is directly proportional to the depth of packing, it indirectly affects the removal efficiency of gaseous contaminants. Higher pressure drops also result in more efficient particulate collection.

Table 4-18 presents a procedure that can be used to evaluate packed bed scrubber design, based on the foregoing considerations of packing depth, liquid-to-gas ratio, superficial gas velocities, contact time, and pressure drop.

TABLE 4-18. PACKED BED SCRUBBER EVALUATION PROCEDURE

1. Is the proposed packing depth sufficient to attain the desired gas absorption efficiency? See Table 4-17[a].

2. Is the proposed liquid-to-gas ratio within normal limits, as described in the preceding discussion?

3. Is the superficial gas velocity through the scrubber reasonable, based on the preceding discussion? (Worksheet 4-7 shows how superficial gas velocities may be calculated for incinerators. The same procedure may be used for scrubber velocity calculation.)

4. Are the contact times and pressure drops through the scrubber reasonable, based on the preceding discussion? (Contact time can be estimated using the methods shown in Worksheet 4-6 for incinerator gas residence time, replacing the incinerator volume term with the total volume occupied by the packed section of the scrubber:

$$V_p = Z \left(\frac{\pi D^2}{4}\right)$$

where Z = bed depth and D = column diameter.)

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[a] Table 4-17 is only applicable for highly soluble gases such as HCl and HF. If other gaseous pollutants are to be removed, technical assistance may be requested.

4.4.2.3 Plate Tower Scrubbers--

Plate towers are vertical cylindrical columns with a number of plates or trays inside. The scrubbing liquid is introduced at the top plate and flows successively across each plate as it moves downward to the liquid outlet at the tower bottom. Gas comes in at the bottom of the tower and passes through openings in each plate before leaving through the top. Gas absorption is promoted by the breaking up of the gas phase into small bubbles which pass through the volume of liquid on each plate. Water, caustic solution, and lime solution can all be used as the scrubbing liquid.

The primary design variables for gas absorption in plate tower scrubbers are the number of plates or trays, the liquid-to-gas ratio, and the contact time. Pressure drop is also an important design criteria although it does not directly affect absorption efficiency. Like packed bed scrubbers, plate tower scrubbers can be used for limited particulate collection as well as gas absorption, but they are not primarily designed for this purpose.

Number of plates--In the design of plate towers for absorption of gaseous contaminants that are highly soluble or chemically reactive with the scrubbing liquid, the number of actual plates, N_p, may be calculated from the equation [6]:

$$N_p = - \frac{\ln(y_1/y_2)}{\ln(1-E_{MV})}$$

where y_1 and y_2 are the inlet and outlet concentrations of the gaseous contaminant and E_{MV} is the Murphree vapor phase efficiency. In developing the above equation, the assumption is made that E_{MV} is the same for each plate in the tower. The Murphree vapor phase efficiencies for the various plate designs may be obtained from published data for selected gas-liquid systems [6,17]. These would normally be in the 25% to 80% range. A rigorous estimation of the Murphree vapor phase efficiency is extremely complex. For the case of absorption towers operating with low viscosity liquids and without excessive weepage (liquid dripping) or entrainment, the figures in Table 4-19 can be used.

TABLE 4-19. MURPHREE VAPOR PHASE EFFICIENCY FOR PLATE TOWERS [19]

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Perforation diameter, in.	Murphree vapor phase efficiency, percent
1/16	80
1/16 to 1/8	75
1/8 to 3/16	70
1/4 to 3/8	65

Liquid-to-gas ratio--For plate towers, the selection of the optimum liquid-to-gas ratio depends largely on operating experience. Experience has indicated that for single-pass crossflow bubble cap trays, the liquid flow should not exceed 0.72d ft^3/s, where d is the diameter of the tower in feet. Since the gas flow rate in the tower can be estimated from the Souders-Brown equation, the maximum liquid-to-gas ratio is given as follows:

$$\left(\frac{\text{Liquid}}{\text{Gas}}\right)_{max} = \frac{630}{Kd}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{0.5}, \text{gal/1,000 ft}^3$$

where K is an empirical constant in the Souders-Brown equation, and ρ_G and ρ_L are the gas and liquid densities, respectively. Values of K are available from Chemical Engineers' Handbook [6] or any other standard chemical engineering reference on mass transfer, distillation, or unit operations. For towers with a tray spacing of 24 in., K is typically 0.17.

Contact time--As in packed bed scrubbers, gas/liquid contact time is an important factor affecting removal efficiency. In tray towers, greater depths of liquid on the plates lead to greater plate efficiency through longer contact time with the gas. Typical gas residence times in tray towers are comparable to those for packed bed scrubbers; for example, 0.4 s to 0.6 s for 99+% absorption of HCl in caustic solution. For absorption of SO_2 by lime solution, longer contact times (in the range of 3-9 s) are needed to overcome the additional mass transfer resistance due to solids dissolution.

Pressure drop--For plate towers, the pressure drop across a perforated plate is the sum of the gas resistance in passing through the perforations plus the head required to overcome the equivalent liquid depth on the plate:

$$\Delta P = \Delta P_h + h_L$$

P_h, the pressure drop due to gas resistance in in. WG, can be calculated from the equation [20]:

$$\Delta P_h = 2.0 \left(\frac{\rho_G}{\rho_L}\right)\left(\frac{U_o}{C_{vo}}\right)^2$$

where ρ_G and ρ_L are the gas and liquid densities, respectively; U_o is the linear velocity of the gas through perforations in ft/s; and C_{vo} is the orifice coefficient. Values of C_{vo} are 0.7-0.8 for sieve trays and 0.6-0.7 for bubble cap trays. The pressure drop due to liquid head in in. WG, h_L, can be calculated from a knowledge of weir dimensions:

$$h_L = 1.5 \times 10^{-7} \rho_L (h_w + h_{ow})$$

where ρ_L is the liquid density in lb/ft^3, h_w is height of weir on the tray in mm, and h_{ow} is height of weir crest in mm.

Total pressure drop can be roughly estimated by:

$$\Delta P_T = \Delta P_p \times N_p$$

where ΔP_T = total pressure drop

ΔP_p = pressure drop per plate

N_p = number of plates

Table 4-20 presents a procedure that can be used for plate tower scrubber design evaluation, based on consideraton of the number of plates required, liquid-to-gas ratio, contact time, and pressure drop. The equations presented above can be used to estimate pressure drop if this information is not available from the vendor. However, vendor data are preferable.

TABLE 4-20. PLATE TOWER SCRUBBER EVALUATION PROCEDURE

1. Are the proposed number of plates comparable to or greater than the required number of plates, as estimated by the procedures shown in Worksheet 4-14[a].
2. Are the proposed liquid flow and liquid-to-gas ratio reasonable and less than the maximum acceptable values calculated by the methods shown in Worksheet 4-15?
3. Are the contact time and pressure drop within reason?

[a] This procedure is only valid for gases highly soluble in the scrubber liquor.

4.4.3 Quenching and Mist Elimination Considerations

In addition to scrubbers used for particulate and gaseous emission control, air pollution control systems for hazardous waste incinerators frequently include quench towers and mist eliminators. Located upstream from the scrubbers, quench towers are designed to reduce the temperature of the combustion gases leaving the incinerator. This temperature reduction reduces the volumetric gas flow rate, and thus the scrubber capacity requirement. Quenching also reduces evaporative water losses in the scrubber, and allows the use of low temperature materials of construction such as fiber-reinforced plastic (FRP) rather than more expensive, high temperature alloys or refractory.

Since venturi scrubbers provide evaporative gas cooling by the very nature of their design, quenching may be considered optional when these devices are used for primary particulate and/or gaseous emission control. Packed bed and plate tower scrubbers, however, are not designed for evaporated cooling. When these devices are used without upstream venturi scrubbing, quenching is nearly always required. Without quenching, evaporative water loss from caustic or lime solution can lead to particulate emissions of sodium or calcium salts.

At existing hazardous waste incineration facilities, combustion gases are normally quenched to temperatures of 120-300°F, and below 200°F for FRP scrubber construction. Typical water consumption rates for quenching are in the range of 0.75 to 3.75 gal/1000 ft^3 (0.1 to 0.5 L/m^3) of gas.

Mist eliminators are widely used to reduce emissions of liquid droplets from scrubbers. Mist eliminators are normally installed downstream from, or as an integral part of, the scrubbing system. In general, only one mist eliminator is needed. Where two or more scrubbers are used in series, intermediate mist elimination may be provided, but it is not considered necessary to prevent the release of liquid droplets to the environment.

The types of mist eliminators most commonly used in hazardous waste incineration facilities are cyclone collectors, simple inertial separators such as baffles, wire mesh mist eliminators, and fiber bed mist eliminators. Cyclones are used for collecting very heavy liquid loadings of droplets over 10 μm, such as those emitted from venturi scrubbers. The design of cyclone mist eliminators follows the principles of cyclone design for particles. For this type of mist eliminator, therefore, the collection efficiencies for liquid droplets and solid particles are about the same. Collection efficiencies of nearly 100% are possible for droplets in the 10- to 50-μm range, which is consistent with the liquid droplet sizes emitted from venturi scrubbers.

In the simple inertial separators, the primary collection mechanism is inertial impaction, and to a lesser extent interception. Devices such as louvers, zigzag baffles, tube banks, and chevrons are simple inertial separators. The cut diameter for liquid droplet collection in these devices is typically 10 μm. Pressure drops are in the 0.02- to 0.12-in. WG (50-to 300-Pa range) depending on the gas velocity and closeness in spacing of the collection surfaces.

Wire mesh eliminators are formed from meshes of wire knitted into a cylindrical open weave which is then crimped to give a stable wire configuration. As rising mist droplets contact the wire surface, they flow down the wire to a wire junction, coalesce, run off, and flow freely to the bottom of the bed. The depth of the wire pad varies from 2 to 12 in. (50 to 300 mm) with 4-6 in. pads being the most common. Pressure drops usually range from 0.02 to 4.0 in. WG, depending on the gas velocity, the wire density, and the depth of the pad. In normal operation, the pressure drop is not likely to be more than 1 in. WG. The cut diameter for liquid droplet collection is a strong function of the gas velocity, and can range from 1 to 10 μm. Sizing of the wire mesh mist eliminator is based on the allowable gas velocity, calculated using the Souders-Brown equation:

$$u = 0.107 \sqrt{\frac{\rho_L - \rho_G}{\rho_G}}$$

Where u is the gas velocity in m/s, ρ_L is the density of the scrubbing liquid, and ρ_G is the gas density.

For collection of fine acid mists, fiber bed mist eliminators are most appropriate. In this type of device, large mist particles are collected on the fibers by inertial impaction and direct interception, whereas smaller particles are collected by Brownian diffusion. Since fiber bed mist eliminators are designed so that Brownian diffusion is the predominant mechanism for mist collection, extremely small particles of less than 1 μm are recovered with high efficiency. Typical gas velocities through fiber bed mist eliminators range from 5 to 10.0 ft/s (1.5 to 30 m/s), with corresponding pressure drops of 5 to 15 in. WG. Collection efficiencies are 100% for droplets larger than 3 μm, and 90% to 99.5% for droplets less than 3 μm.

In wire mesh and fiber bed mist eliminators, plugging by solid deposition is a potential problem. This problem can be partially overcome by intermittent washing with sprays, by selection of a less densely packed design, and by the use of sieve plate towers or cyclone separators upstream as an additional mist and particle collection device. At hazardous waste incineration facilities, the most common configuration used for gas cleanup is a high energy venturi scrubber followed by two sieve trays for additional gas absorption, and then another sieve tray and an inertial separator or a wire mesh eliminator to reduce emissions of liquid droplets. Operating experience has indicated that this is a most effective combination.

In general, three "rules of thumb" can be followed in evaluating provisions for quenching and mist elimination at hazardous waste incineration facilities.

- Quenching should be provided upstream from packed bed or plate tower scrubbers unless these devices are preceded by a venturi scrubber.
- Quenching is optional when venturi scrubbers are used, although high temperature materials of construction may be required if quenching is not employed.
- A mist eliminator should be provided downstream or as an integral part of the last scrubber in the air pollution control system.

4.4.4 Prime Mover Capacity Evaluation

Prime movers in rotary kiln incineration systems are always induced draft fans, located downstream from the air pollution control devices, while either induced draft or forced draft systems may be used with liquid injection incinerators. For the overall system to function properly, the prime mover must be capable of moving the combustion gases through each air pollution control device while overcoming the corresponding pressure drops. As the total pressure drop through the system increases, the volumetric flow capacity of the fan decreases. The functional relationship between these two variables, pressure and flow capacity at a specific temperature, should be specified by the manufacturer.

Therefore, it is necessary to (a) determine the combustion gas flow rate at the fan inlet temperature, (b) estimate the total pressure drop across the system, and (c) compare the fan capacity at the calculated pressure drop with the predetermined combustion gas flow rate in order to evaluate whether or not the fan has sufficient gas handling capacity. If this capacity is insufficient the burning rate must be decreased, the fan capacity must be increased, or the ductwork must be modified to reduce pressure drop. The following discussion focuses on Step (b) above, estimation of the total system pressure drop. Combustion gas flow rate calculations are discussed in Section 4.3.2.

The major pressure drops to be considered are the pressure drops across the various air pollution control devices. These pressure drops can be determined from manufacturer specifications once the gas flow rates at the inlets to these devices are known. Flow rates can be calculated quite simply as follows:

$$q = \frac{q_{std}}{P}\left(\frac{T + 460}{528}\right)$$

where q = combustion gas flow rate, acfm

q_{std} = combustion gas flow rate, at standard conditions of 68°F and 1 atm, scfm (from Worksheet 4-2 or 4-4)

T = inlet temperature, °F

P = combustion gas static pressure, atm

Other pressure drops that need to be considered are frictional losses due to flow through the ductwork connecting each air pollution control device. For any given duct, the total pressure drop may consist of three component pressure drops: (1) frictional losses due to flow through straight lengths of ductwork, (2) frictional losses due to flow through bends in the ductwork, and (3) losses due to sudden constriction of flow at the inlet to the duct.

Pressure drop through a straight length of duct can be estimated using Figure 4-16, reproduced from Reference 6. This figure can be used in the following manner:

(1) Identify the temperature and average molecular weight of the gas.

(2) Draw a line through these two points on the temperature and molecular weight scales, and extrapolate this line to a point on the viscosity scale.

(3) Identify the inside diameter of the duct and the mass flow of combustion gases.

(4) Draw a line through these two points on the diameter and weight flow scales, and extrapolate this line to the arbitrary reference scale.

(5) Connect the point on the arbitrary reference scale with the predetermined point on the viscosity scale.

(6) Identify the pressure drop per foot of duct on the ΔP scale at the intersection of the line between the reference and viscosity scales.

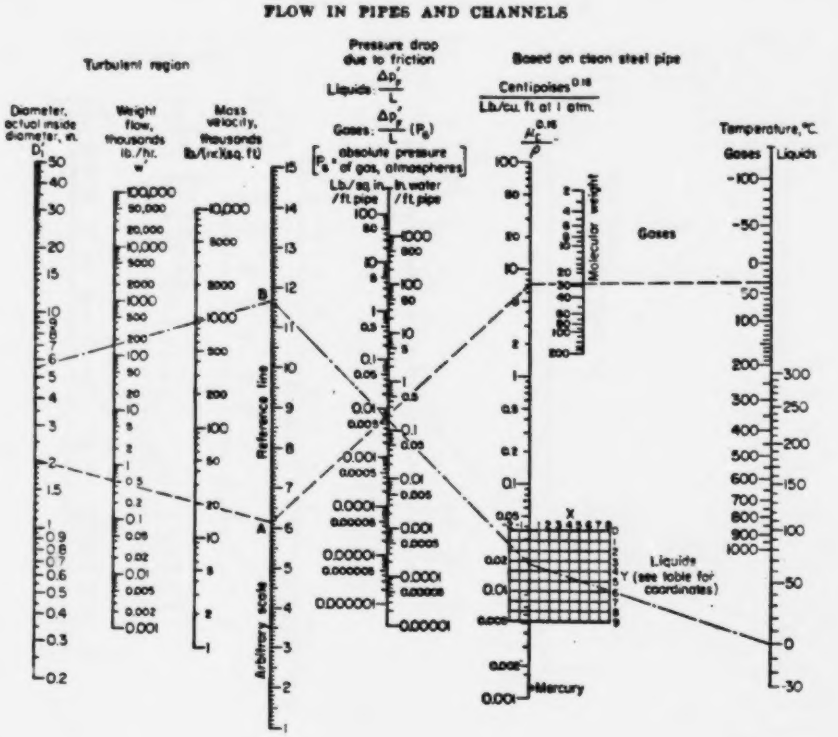

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Figure 4-16. Pipe flow chart [6].

(7) Calculate the total pressure drop across the length of straight duct as follows:

$$\Delta P = \frac{\Delta P}{L}(P_G)^{a} \quad L_S$$

where ΔP = total pressure drop, in. H_2O

L_S = length of straight duct, ft

P_G = absolute gas pressure, atm

For a reasonable approximation, assume

$$P_G \cong 1 \text{ atm}$$

---

[a] From Figure 4-13.

If the duct is square or rectangular the following quantities should be used as equivalent diameters:

Square duct: D_{eq} = length of a side

Rectangular duct: $D_{eq} = \frac{2\,ab}{a + b}$

where a, b = width and depth of the duct

Pressure drops across bends in a duct can be estimated using Figure 4-17. Here, L_e/D, the equivalent straight-length-to-diameter ratio, is expressed as a function of the ratio of the radius of curvature of the elbow, R, to the diameter of the duct. Figure 4-18 shows the relationship between R and D.

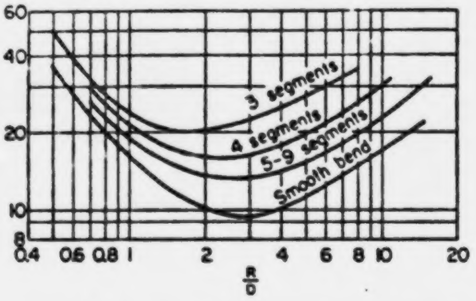

Figure 4-17. Total frictional pressure drops in 90° bends [6].

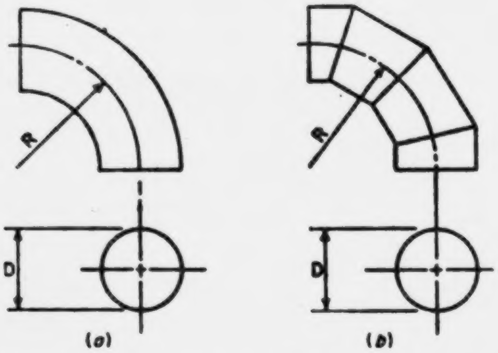

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Figure 4-18. 90° bends (a) smooth bend, (b) segmental bend [6].

The procedure for estimating pressure drops from Figure 4-14 is as follows:

(1) Determine R/D and read the corresponding L_e/D value from Figure 4-14.

(2) Identify the pressure drop across the length of straight duct upstream and downstream from the bend and the corresponding length of straight duct.

(3) Convert the L_e/D value to a pressure drop estimate:

$$\Delta P' = \Delta P \left(\frac{L_e}{D}\right)\left(\frac{12\ D}{L_S}\right)$$

where $\Delta P'$ = pressure drop across the bend, in. H_2O
ΔP = pressure drop across the straight segment of duct, in. H_2O
D = diameter of the duct, in.
L_S = length of straight duct, ft

If 45° or 180° angle bends are encountered, the corrected pressure drops are:

$$\Delta P'_{45°} = 0.65\ \Delta P'_{90°}$$

and

$$\Delta P'_{180°} = 1.4\ \Delta P'_{90°}$$

Additional pressure drops occur at the inlet to a duct because of the sudden contraction of the gases. These pressure drops can be estimated by the following equation:

$$\Delta P'' = 6\ K_c \left(\frac{V^2}{g_c}\right)\left(\frac{\rho_{gas}}{\rho_{H_2O}}\right)$$

where $\Delta P''$ = pressure drop, in. H_2O
V = gas velocity, ft/s
g_c = gravitational constant, 32.2 lb-m ft/lb-f s^2
ρ_{gas} = gas density, lb/ft^3
ρ_{H_2O} = density of liquid water, 62.4 lb/ft^3
K_c = sudden contraction-loss coefficient for turbulent flow

Table 4-21 presents K_c values for various ratios of duct cross-sectional area, A_d, to the cross-sectional area of the unit upstream from the duct, A_p.

When the pressure drops through each air pollution control device and segment of ductwork are calculated and summed, this should provide a rough estimate of the total pressure drop through the system.

Table 4-22 presents a procedure for evaluating the prime gas mover capacity. A step-by-step method for performing the necessary calculations is shown in Worksheet 4-16.

TABLE 4-21. SUDDEN CONTRACTION-LOSS COEFFICIENT FOR TURBULENT FLOW [6]

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A_d/A_p	0	0.2	0.4	0.6	0.8	1.0
K_c	0.5	0.45	0.36	0.21	0.07	0

TABLE 4-22. PRIME MOVER CAPACITY EVALUATION PROCEDURE

1. Identify the approximate combustion gas flow rate in scfm (see Worksheet 4-2 or 4-4).

2. Identify the temperatures at (a) the incinerator outlet, (b) the inlet to each air pollution control device, and (c) the fan inlet. Record this information on Worksheet 4-16.

3. Identify the pressure drops across each air pollution control device, as specified by the manufacturer, and record this information on Worksheet 4-16.

4. Estimate the pressure drops across each segment of ductwork between the incinerator and the fan, and add these pressure drops to those determined in checkpoint #3 to estimate the total pressure drop across the system.

5. Identify the manufacturer specifications for fan capacity at the calculated pressure drop and fan inlet temperature.

6. Does this capacity meet or exceed the approximate combustion gas flow rate?

4.4.5 Process Control and Automatic Shutdown System Evaluation

In the design of the incinerator and scrubber systems, a number of safety features should be provided to allow for equipment failures and operational errors. Process control systems and safety interlocks for incinerators are discussed in Section 4.3.5. The following safety interlocks relating to the scrubber operation are recommended:

(1) Shutdown of the waste and auxiliary fuel feed systems on loss of scrubber water flow.

(2) Shutdown of the waste and auxiliary fuel feed systems if the incinerator effluent gas temperature exceeds the maximum design temperature for the quench section.

(3) Shutdown of the waste and auxiliary fuel feed systems if the quenched gas temperature exceeds the maximum design temperature for the scrubber.

(4) Shutdown of the waste and auxiliary fuel feed systems, followed by shutdown of the scrubber systems, on failure of forced or induced draft fan.

(5) Shutdown of the waste and auxiliary fuel feed systems followed by shutdown of the scrubber systems, if the pH of the scrubbing liquid does not meet specified values.

(6) Shutdown of the waste and auxiliary fuel feed systems, followed by shutdown of the scrubber systems, if the pressure drop across the scrubber becomes excessive, indicating unsteady-state operation or clogging problems.

When possible, it is desirable to have a time delay between shutting off the waste to be incinerated and shutting off the auxiliary fuel. This will help to ensure an adequate burnout of the waste and minimize emissions of incomplete products of waste combustion and unreacted waste.

In situations when the incinerator effluent gas temperature or the quenched gas temperature exceeds the maximum design temperature for the next piece of equipment, it is desirable to have provisions for emergency stack bypass designed into the system. An indication of excess temperature should lead to shutdown of the incinerator through the safety interlock system. It is recognized, however, that any of the interlock devices can and will malfunction some of the time. To protect the scrubber system from damage by excess temperature, switches for stack bypass can be provided. These switches should only be operated as an emergency measure, and under strict supervision. To a limited extent, the additional thermal lift caused by the excess temperature will raise the effective stack height and alleviate the impact on plant personnel.

At power plants, chemical plants, and refineries, stack bypass switches are often provided to enable maintenace to be done on scrubber systems while process operation continues. Stack bypass for maintenance purposes is not recommended for hazardous waste incineration facilities.

4.4.6 Material of Construction Considerations

Effluent gases from incineration of hazardous wastes contain a number of corrosive contaminants, including HCl, SO_2, SO_3, HF, and possibly Cl_2, HBr, Br_2, P_2O_5, and organic acids. The presence of HCl, the principal gaseous contaminant, is of particular concern because it accelerates pitting and crevice corrosion of most materials. The careful selection of the materials of construction for the quench tower and scrubber system is therefore extremely important.

In the quench section where temperatures of approximately 1800°F are commonly encountered, Hastelloy C and Inconel 625 have found wide acceptance. Other possibilities are the use of carbon graphite or acid resistant refractories as lining material for carbon steel or stainless steel construction, but the quench spray nozzles should still be made of Hastelloy C or Inconel 625.

For the scrubber, Hastelloy C or Inconel 625 can again be used as materials of construction. At more moderate temperatures, however, FRP is recommended because it is economical, easily fabricated, and lightweight. It also has good resistance in both acid and alkaline environments, up to a service temperature of around 200°F. Polyvinyl chloride (PVC) can also be considered as a material for wet scrubber construction, but its use is limited to temperatures of less than 160°F.

If structural strength becomes a prime consideration because of the size and weight of the scrubber, carbon steel or stainless steel can be used with a suitable lining material to provide the required corrosion protection. Field corrosion studies have shown that carbon steel and stainless steel both experienced severe corrosion problems and are not recommended as materials of construction for scrubber systems treating acid gases unless linings are used. Rubber, carbon graphite, FRP, Teflon, Kynar (polyvinylidene fluoride), acid resistant bricks, and refractories are examples of suitable lining materials. Teflon, however, cannot be bonded to a metal surface and requires multiple flanges to stay in place. Kynar is similar to Teflon in most of its properties, but it is available in sheet form bonded to a glass backing. In packed beds, the packing material should be made of ceramic, carbon, or plastics to withstand attack by corrosive acids.

A special concern is the potential presence of HF in the incinerator exhaust gases. It is well known that glass and any ceramic material containing silica are attacked by HF or H_2SiF_6. Many grades of rubber linings also contain silica as a filler, which could be leached out by HF or H_2SiF_6. Common materials of construction of HF scrubbers include FRP (with special shielding material to prevent attack of the glass fibers), rubber-lined steel, Kynar, and graphite-lined steel. Among the metals, monel has shown good resistance over wide concentration and temperature ranges. At one hazardous waste incineration facility, a Monel-lined stainless steel packed tower with polypropylene Intalox saddles is used to control HF emissions from the incinerator. In addition, both Hastelloy C and Inconel 625 have been used as lining material in hydrofluoric acid service and have demonstrated outstanding corrosion resistance to HF.

Although the corrosion and temperature aspects of materials selection are of primary importance, erosion must also be considered in scrubbers designed for particulate control. Venturi scrubbers are particularly susceptible to erosion due to the high gas velocities and particulate loadings encountered during normal duty. Throat and elbow areas are generally subject to the most wear. FRP does not stand up well in these regions and harder, corrosion resistant, materials are required for long service life.

All the foregoing factors should be considered in evaluating materials selection for the quench tower and scrubber system. If materials of construction other than those discussed above are proposed, the adequacy of these materials for the temperature/gas environment under consideration should be evaluated.

4.5 WORKSHEETS

The worksheets in this section can be used to perform the design evaluation calculations described in Sections 4.3 through 4.4.

WORKSHEET 4-1. PROCEDURE TO CALCULATE DESTRUCTION AND REMOVAL EFFICIENCY

1. From trial burn data, identify the following parameters:

Total waste feed rate, $(W_{in})_{TOTAL}$ = ____________ lb/hr

Mass fraction of each puncysal organic hazardous constituent in the waste,

n_1 = ____________ lb/lb waste
n_2 = ____________ lb/lb waste
n_3 = ____________ lb/lb waste
n_4 = ____________ lb/lb waste
n_5 = ____________ lb/lb waste

Gas flow rate in the stack, q = ____________ scfm

Concentration of each principal organic hazardous constituent in the stack gas,

c_1 = ____________ µg/scf
c_2 = ____________ µg/scf
c_3 = ____________ µg/scf
c_4 = ____________ µg/scf
c_5 = ____________ µg/scf

2. Calculate the mass feed rate of each hazardous constituent to the incinerator, using the following equation:

$$(W_{in})_i = n_i \, (W_{in})_{TOTAL}$$

$(W_{in})_1$ = ____________ lb/hr
$(W_{in})_2$ = ____________ lb/hr
$(W_{in})_3$ = ____________ lb/hr
$(W_{in})_4$ = ____________ lb/hr
$(W_{in})_5$ = ____________ lb/hr

3. Calculate the mass flow rate of each hazardous constituent in the stack using the following equation:

$$(W_{out})_i = \frac{q \, C_i}{7.57 \times 10^6}$$

$(W_{out})_1$ = ____________ lb/hr
$(W_{out})_2$ = ____________ lb/hr
$(W_{out})_3$ = ____________ lb/hr
$(W_{out})_4$ = ____________ lb/hr
$(W_{out})_5$ = ____________ lb/hr

4. Calculate the destruction and removal efficiency for each hazardous constituent using the following equation:

$$DRE_i = \frac{(W_{in})_i - (W_{out})_i}{(W_{in})_i} \quad (100)$$

DRE_1 = ____________ %
DRE_2 = ____________ %
DRE_3 = ____________ %
DRE_4 = ____________ %
DRE_5 = ____________ %

WORKSHEET 4-2. PROCEDURE TO CALCULATE STOICHIOMETRIC AIR REQUIREMENTS, COMBUSTION GAS FLOW, AND COMPOSITION (LIQUID INJECTION INCINERATION)

1. Identify the elemental composition and moisture content of the waste or waste mixture.

Carbon, C_w: ________ lb/lb waste
Fuel hydrogen, H_w: ________ lb/lb waste
Moisture, H_2O_w: ________ lb/lb waste
Oxygen, O_w: ________ lb/lb waste
Nitrogen, N_w: ________ lb/lb waste
Chlorine, Cl_w: ________ lb/lb waste
Fluorine, F_w: ________ lb/lb waste
Bromine, Br_w: ________ lb/lb waste
Iodine, I_w: ________ lb/lb waste
Sulfur, S_w: ________ lb/lb waste
Phosphorus, P_w: ________ lb/lb waste

2. If auxiliary fuel is to be burned in conjunction with the waste, identify the fuel type and approximate, proposed fuel-to-waste ratio from the permit application. (If auxiliary fuel is to be used only for startup, proceed to Step #5.)

Fuel type: ________
Fuel:waste ratio, n_f = ________ lb fuel/lb waste

3. Determine the approximate elemental composition of the fuel from the following table.

	lb Component/lb fuel [21]		
Component	Residual fuel oil (e.g., No. 6)	Distillate fuel oil (e.g., No. 2)	Natural gas
C_f	0.866	0.872	0.693
H_f	0.102	0.123	0.227
N_f	-	-	0.08
S_f	0.03	0.005	-

4. Calculate the composition of the combined waste/auxiliary fuel feed.

C: $\frac{C_w + n_f C_f}{1 + n_f}$ = ________ lb/lb feed

H: $\frac{H_w + n_f H_f}{1 + n_f}$ = ________ lb/lb feed

H_2O: $\frac{H_2O_w}{1 + n_f}$ = ________ lb/lb feed

N: $\frac{N_w + n_f N_f}{1 + n_f}$ = ________ lb/lb feed

O: $\frac{O_w}{1 + n_f}$ = ________ lb/lb feed

Cl: $\frac{Cl_w}{1 + n_f}$ = ________ lb/lb feed

F: $\frac{F_w}{1 + n_f}$ = ________ lb/lb feed

Br: $\frac{Br_w}{1 + n_f}$ = ________ lb/lb feed

I: $\frac{I_w}{1 + n_f}$ = ________ lb/lb feed

S: $\frac{S_w + n_f S_f}{1 + n_f}$ = ________ lb/lb feed

P: $\frac{P_w}{1 + n_f}$ = ________ lb/lb feed

5. Calculate the stoichiometric oxygen requirement based on the combustion reactions described in Section 4.3.2.1.

$C \times 2.67 \frac{\text{lb } O_2}{\text{lb C}}$ = ________ lb O_2/lb feed

$(H - \frac{Cl}{35.5} - \frac{F}{19}) \times 8.0 \frac{\text{lb } O_2}{\text{lb H}}$ = ________ lb O_2/lb feed

$S \times 1.0 \frac{\text{lb } O_2}{\text{lb S}}$ = ________ lb O_2/lb feed

$P \times 1.29 \frac{\text{lb } O_2}{\text{lb P}}$ = ________ lb O_2/lb feed

-O(in feed) = -________ lb O_2/lb feed

$(O_2)_{\text{stoich}} = \Sigma =$ ________ lb O_2/ lb feed

6. Calculate the combustion gas mass flows, based on the stoichiometric oxygen requirement.

CO_2: $C \times 3.67 \frac{\text{lb } CO_2}{\text{lb C}}$ = ___ lb CO_2/lb feed

H_2O: $\left[\left(H - \frac{Cl}{35.5} - \frac{F}{19}\right) \times 9.0 \frac{\text{lb } H_2O}{\text{lb H}}\right] + H_2O\text{(in feed)}$ = ___ lb H_2O/lb feed

N_2: $\left[(O_2)_{stoich} \times 3.31 \frac{\text{lb } N_2}{\text{lb } O_2} \text{ (in air)}\right] + N\text{(in feed)}$ = ___ lb N_2/lb feed

HCl: $Cl \times 1.03 \frac{\text{lb HCl}}{\text{lb Cl}}$ = ___ lb HCl/lb feed

HF: $F \times 1.05 \frac{\text{lb HF}}{\text{lb F}}$ = ___ lb HF/lb feed

Br_2: Br = ___ lb Br_2/lb feed

I_2: I = ___ lb I_2/lb feed

SO_2: $S \times 2.0 \frac{\text{lb } SO_2}{\text{lb S}}$ = ___ lb SO_2/lb feed

P_2O_5: $P \times 2.29 \frac{\text{lb } P_2O_5}{\text{lb P}}$ = ___ lb P_2O_5/lb feed

---

Combustion products = CP = $\sum$ = _______ lb/lb feed

7. Identify the total excess air rate.

EA = ______%/100

8. Calculate the additional nitrogen and oxygen present in the combustion gases due to excess air feed.

$(O_2)_{EA} = EA \times (O_2)_{stoich}$ = ________ lb O_2/lb waste

$(N_2)_{EA} = 3.31 \frac{\text{lb } N_2}{\text{lb } O_2} \text{ (in air)} \times (O_2)_{EA}$ = _____ lb N_2/lb waste

9. Calculate the total combustion gas flow.

Combustion gases = CG = CP + $(O_2)_{EA}$ + $(N_2)_{EA}$ = _______ lb/lb waste

10. Calculate the mass fraction of each combustion gas component.

CO_2: $\frac{CO_2}{CG}$ = _________ lb/lb gas

H_2O: $\frac{H_2O}{CG}$ = _________ lb/lb gas

N_2: $\frac{N_2(\text{from \#6}) + (N_2)_{EA}}{CG}$ = __________ lb/lb gas

O_2: $\frac{(O_2)_{EA}}{CG}$ = __________ lb/lb gas

HCl: $\frac{HCl}{CG}$ = __________ lb/lb gas

HF: $\frac{HF}{CG}$ = __________ lb/lb gas

Br_2: $\frac{Br_2}{CG}$ = __________ lb/lb gas

I_2: $\frac{I_2}{CG}$ = __________ lb/lb gas

SO_2: $\frac{SO_2}{CG}$ = __________ lb/lb gas

P_2O_5: $\frac{P_2O_5}{CG}$ = __________ lb/lb gas

11. Identify those components that constitute less than 1-2% of the combustion gas. These components can be eliminated from further consideration in heat and material balance calculations. In most cases, CO_2, H_2O, N_2, and O_2 will be the only combustion gas components that need to be considered.

12. Calculate the volumetric flow of the major combustion products at standard conditions of 68°F and 1 atm.

CO_2: $\frac{CO_2}{CG} \times CG \div 0.114 \frac{lb}{scf}$ = __________ scf/lb feed

H_2O: $\frac{H_2O}{CG} \times CG \div 0.0467 \frac{lb}{scf}$ = __________ scf/lb feed

N_2: $\frac{N_2}{CG} \times CG \div 0.0727 \frac{lb}{scf}$ = __________ scf/lb feed

O_2: $\frac{O_2}{CG} \times CG \div 0.083 \frac{lb}{scf}$ = __________ scf/lb feed

Other: $\frac{\text{Other}}{CG} \times CG \div (0.00259\ M)\frac{lb}{scf}$ = __________ scf/lb feed

where M = molecular weight

Total flow, q = = __________ $\frac{scf}{lb\ feed}$

$q \times m_{feed}$ (lb/hr) ÷ 60 = __________ scfm

WORKSHEET 4-3. PROCEDURE TO CALCULATE THE NET HEATING VALUE[a] OF THE WASTE

Basis: Heating value is reported as a higher heating value (HHV) determined at standard 77°F (25°C).

Identify the following:

HHV = ______________________ Btu/lb waste
H = ______________________ lbH/lb waste
Cl = ______________________ lbCl/lb waste
F = ______________________ lbF/lb waste
H_2O = ______________________ lb/moisture/lb waste

Calculate the net heating value (NHV):

$$NHV = HHV - 1{,}050\left[H_2O + 9\left(H - \frac{Cl}{35.5} - \frac{F}{19}\right)\right] = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{ Btu/lb waste}$$

---

[a] Heating value: The quantity of heat released when waste is burned, commonly expressed as Btu/lb. The higher heating value includes the heat of condensation of the water present in the waste and the heat formed in the combustion reaction; the lower heating vfalue represents the heat formed in the combustion reaction; and the net heating value is the lower heating value minus the energy necessary to vaporize any moisture present.

WORKSHEET 4-4. PROCEDURE TO CALCULATE STOICHIOMETRIC AIR REQUIREMENTS, APPROXIMATE COMBUSTION GAS FLOWS, AND APPROXIMATE GAS COMPOSITIONS (ROTARY KILNS)

1. Identify the elemental composition and moisture content of the wastes fed to the kiln.

	1. Solids (kiln)	2. Liquids (kiln)	
Carbon, C_w:	______	______	lb/lb waste
Fuel hydrogen, H_w:	______	______	lb/lb waste
Moisture, H_2O_w:	______	______	lb/lb waste
Oxygen, O_w:	______	______	lb/lb waste
Nitrogen, N_w:	______	______	lb/lb waste
Chlorine, Cl_w:	______	______	lb/lb waste
Fluorine, F_w:	______	______	lb/lb waste
Bromine, Br_w:	______	______	lb/lb waste
Iodine, I_w:	______	______	lb/lb waste
Sulfur, S_w:	______	______	lb/lb waste
Phosphorus, P_w:	______	______	lb/lb waste

2. Identify the approximate liquid and solid waste feed rates to the kiln, and calculate the liquid/solid feed fractions.

Liquid feed rate, m_1 = ______ lb/hr

Solid feed rate, m_2 = ______ lb/hr

Total feed, $m_{12} = m_1 + m_2$ = ______ lb/hr

Liquid fraction, $n_1 = m_1/m_{12}$ = ______ lb liquid/lb waste

Solid fraction, $n_2 = 1-n_1$ = ______ lb solid/lb waste

3. If auxiliary fuel is to be burned in conjunction with the wastes, identify the fuel type and approximate, proposed fuel-to-waste ratio.

Fuel type: ______
Fuel:waste ratio in kiln: n_{fK} = ______ lb fuel/lb waste

4. Determine the approximate elemental composition of the fuel from the following table.

	lb component/lb fuel [21]		
Component	Residual fuel oil (e.g. No. 6)	Distillate fuel oil (e.g. No. 2)	Natural gas
C_f	0.866	0.872	0.693
H_f	0.102	0.123	0.227
N_f	-	-	0.08
S_f	0.03	0.005	-

5. Calculate the composition of the combined waste/auxiliary fuel feed to the kiln.

C_k: $\dfrac{n_1C_1 + n_2C_2 + n_fC_f}{1 + n_f}$ = ____________________ lb/lb feed

H_k: $\dfrac{n_1H_1 + n_2H_2 + n_fH_f}{1 + n_f}$ = ____________________ lb/lb feed

H_2O_k: $\dfrac{n_1H_2O_1 + n_2H_2O_2}{1 + n_f}$ = ____________________ lb/lb feed

N_k: $\dfrac{n_1N_1 + n_2N_2 + n_fN_f}{1 + n_f}$ = ____________________ lb/lb feed

O_k: $\dfrac{n_1O_1 + n_2O_2}{1 + n_f}$ = ____________________ lb/lb feed

Cl_k: $\dfrac{n_1Cl_1 + n_2Cl_2}{1 + n_f}$ = ____________________ lb/lb feed

F_k: $\dfrac{n_1F_1 + n_2F_2}{1 + n_f}$ = ____________________ lb/lb feed

Br_k: $\dfrac{n_1Br_1 + n_2Br_2}{1 + n_f}$ = ____________________ lb/lb feed

I_k: $\dfrac{n_1I_1 + n_2I_2}{1 + n_f}$ = ____________________ lb/lb feed

S_k: $\dfrac{n_1S_1 + n_2S_2 + n_fS_f}{1 + n_f}$ = ____________________ lb/lb feed

P_k: $\dfrac{n_1P_1 + n_2P_2}{1 + n_f}$ = ____________________ lb/lb feed

6. Calculate the stoichiometric oxygen requirement for the kiln, based on the combustion reactions described in Section 4.3.2.1.

$C_k \times 2.67 \dfrac{\text{lb } O_2}{\text{lb C}}$ = ____________________ lb O_2/lb feed

$\left(H_k - \dfrac{Cl_k}{35.5} - \dfrac{F_k}{19}\right) \times 8.0 \dfrac{\text{lb } O_2}{\text{lb H}}$ = ____________________ lb O_2/lb feed

$S_k \times 1.0 \dfrac{\text{lb } O_2}{\text{lb S}}$ = ____________________ lb O_2/lb feed

$P_k \times 1.29 \frac{\text{lb } O_2}{\text{lb } P}$ = ________________ lb O_2/lb feed

$-O_k$ (in feed) = - ________________ lb/O_2/lb feed

$(O_2)_{\text{stoich}(k)}$ = = ________________ lb O_2/lb feed

7. Calculate the combustion gas mass flows, based on the stoichiometric oxygen requirement (assume complete combustion is achieved for purposes of gas flow estimation).

CO_{2_k}: $C_k \times 3.67 \frac{\text{lb } CO_2}{\text{lb } C}$ = ________ lb CO_2/lb feed

H_2O_k: $\left[\left(H_k - \frac{Cl_k}{35.5} - \frac{F_k}{19}\right) \times 9.0 \frac{\text{lb } H_2O}{\text{lb } H}\right]$

$+ H_2O_k$ (in feed) = ________ lb H_2O/lb feed

N_{2_k}: $\left[(O_2)_{\text{stoich}(k)} \times 3.31 \frac{\text{lb } N_2}{\text{lb } O_2} \text{ (in air)}\right]$

$+ N_k$ (in feed) = ________ lb N_2/lb feed

HCl_k: $Cl_k \times 1.03 \frac{\text{lb } HCl}{\text{lb } Cl}$ = ________ lb HCl/lb feed

HF_k: $F_k \times 1.05 \frac{\text{lb } HF}{\text{lb } F}$ = ________ lb HF/lb feed

Br_{2_k}: Br_k = ________ lb Br_2/lb feed

I_{2_k}: I_k = ________ lb I_2/lb feed

SO_{2_k}: $S_k \times 2.0 \frac{\text{lb } SO_2}{\text{lb } S}$ = ________ lb SO_2/lb feed

$P_2O_{5_k}$: $P_k \times 2.29 \frac{\text{lb } P_2O_5}{\text{lb } P}$ = ________ lb P_2O_5/lb feed

---

Kiln combustion products = $CP_k = \sum =$ ________ lb/lb feed

8. Identify the elemental composition and moisture content of the liquid wastes to be burned in the afterburner (if any).

C_3: __________ lb/lb waste
H_3: __________ lb/lb waste
H_2O_3: __________ lb/lb waste
O_3: __________ lb/lb waste
N_3: __________ lb/lb waste
Cl_3: __________ lb/lb waste
F_3: __________ lb/lb waste
Br_3: __________ lb/lb waste
I_3: __________ lb/lb waste
S_3: __________ lb/lb waste
P_3: __________ lb/lb waste

9. Identify the fuel type and approximate, proposed fuel-to-waste ratio for the afterburner.

Fuel type: ____________________

Fuel: waste ratio, n_{fA} = ____________________ lb fuel/lb waste

10. Determine the approximate elemental composition of the fuel from the table shown in Step 4.

C_{fA} = __________ lb/lb fuel
H_{fA} = __________ lb/lb fuel
N_{fA} = __________ lb/lb fuel
S_{fA} = __________ lb/lb fuel

11. Calculate the composition of the combined waste/auxiliary fuel feed to the afterburner.

C_A: $\frac{C_3 + n_{fA} C_{fA}}{1 + n_{fA}}$ = __________ lb/lb feed

H_A: $\frac{H_3 + n_{fA} H_{fA}}{1 + n_{fA}}$ = __________ lb/lb feed

H_2O_A: $\frac{H_2O_3}{1 + n_{fA}}$ = __________ lb/lb feed

N_A: $\frac{N_3 + n_{fA} N_{fA}}{1 + n_{fA}}$ = __________ lb/lb feed

O_A: $\frac{O_3}{1 + n_{fA}}$ = __________ lb/lb feed

Cl_A: $\frac{Cl_3}{1 + n_{fA}}$ = __________ lb/lb feed

F_A: $\frac{F_3}{1 + n_{fA}}$ = __________ lb/lb feed

Br_A: $\frac{Br_3}{1 + n_{fA}}$ = __________ lb/lb feed

I_A: $\frac{I_3}{1 + n_{fA}}$ = __________ lb/lb feed

S_A: $\frac{S_3 + n_{fA}S_{fA}}{1 + n_{fA}}$ = __________ lb/lb feed

P_A: $\frac{P_3}{1 + n_{fA}}$ = __________ lb/lb feed

12. Calculate the stoichiometric oxygen requirement for the afterburner feed, based on the combustion reactions described in Section 4.3.2.1.

$C_A \times 2.67 \frac{\text{lb } O_2}{\text{lb C}}$ = ________________ lb O_2/lb feed

$\left(H_A - \frac{Cl_A}{35.5} - \frac{F_A}{19}\right) \times 8.0 \frac{\text{lb } O_2}{\text{lb H}}$ = ________________ lb O_2/lb feed

$S_A \times 1.0 \frac{\text{lb } O_2}{\text{lb S}}$ = ________________ lb O_2/lb feed

$P_A \times 1.29 \frac{\text{lb } O_2}{\text{lb P}}$ = ________________ lb O_2/lb feed

$-O_A$ (in feed) = -________________ lb O_2/lb feed

$(O_2)_{stoich(A)} = \sum =$ ________________ lb O_2/lb feed

13. Calculate the combustion gas mass flows, based on the stoichiometric oxygen requirement.

CO_{2_A}: $C_A \times 3.67 \frac{\text{lb } CO_2}{\text{lb C}}$ = ________ lb CO_2/lb feed

H_2O_A: $\left[\left(H_A - \frac{Cl_A}{35.5} - \frac{F_A}{19}\right) \times 9.0 \frac{\text{lb } H_2O}{\text{lb H}}\right]$
+ H_2O_A (in feed) = ________ lb H_2O/lb feed

N_{2_A}: $\left[(O_2)_{stoich(A)} \times 3.31 \frac{\text{lb } N_2}{\text{lb } O_2} \text{ (in air)}\right]$
+ N_A (in feed) = ________ lb N_2/lb feed

HCl_A: $Cl_A \times 1.03 \frac{\text{lb HCl}}{\text{lb Cl}}$ = ________ lb HCl/lb feed

HF_A: $F_A \times 1.05 \frac{\text{lb HF}}{\text{lb F}}$ = ________ lb HF/lb feed

Br_{2_A}: Br_A = ________ lb Br_2/lb feed

I_{2_A}: I_A = ________ lb I_2/lb feed

SO_{2_A}: $S_A \times 2.0 \frac{\text{lb } SO_2}{\text{lb S}}$ = ________ lb SO_2/lb feed

$P_2O_{5_A}$: $P_A \times 2.29 \frac{\text{lb } P_2O_5}{\text{lb P}}$ = ________ lb P_2O_5/lb feed

Afterburner combustion products = $CP_A = \sum =$ ________ lb/lb feed

14. Calculate the ratio of total afterburner feed to total kiln feed.

Liquid waste to kiln: m_1 = __________ lb/hr
Solid waste to kiln: m_2 = __________ lb/hr
Auxiliary fuel to kiln: $(m_1 + m_2)n_{fK}$ = __________ lb/hr

Liquid waste to afterburner: m_3 = __________ lb/hr
Auxiliary fuel to afterburner: $m_3 n_{fA}$ = __________ lb/hr

$n_{AK} = \dfrac{(m_1 + m_2)\ (1 + n_{fK})}{m_3\ n_{fA}}$ = __________ lb afterburner feed/lb kiln feed

15. Calculate the total combustion gas mass flows, based on stoichiometric oxygen requirements.

CO_2: $\dfrac{CO_{2_K} + CO_{2_A}\ n_{AK}}{1 + n_{AK}}$ = __________ lb/lb feed

H_2O: $\dfrac{H_2O_K + n_{AK}\ H_2O_A}{1 + n_{AK}}$ = __________ lb/lb feed

N_2: $\dfrac{N_{2_K} + n_{AK}\ N_{2_A}}{1 + n_{AK}}$ = __________ lb/lb feed

HCl: $\dfrac{HCl_K + n_{AK}\ HCl_A}{1 + n_{AK}}$ = __________ lb/lb feed

HF: $\dfrac{HF_K + n_{AK}\ HF_A}{1 + n_{AK}}$ = __________ lb/lb feed

Br_2: $\dfrac{Br_{2_K} + N_{AK}\ Br_{2_A}}{1 + n_{AK}}$ = __________ lb/lb feed

I_2: $\dfrac{I_{2_K} + n_{AK}\ I_{2_A}}{1 + n_{AK}}$ = __________ lb/lb feed

SO_2: $\dfrac{SO_{2_K} + n_{AK}\ SO_{2_A}}{1 + n_{AK}}$ = __________ lb/lb feed

P_2O_5: $\dfrac{P_2O_{5_K} + n_{AK}\ P_2O_{5_A}}{1 + n_{AK}}$ = __________ lb/lb feed

Combustion products = CP = $\sum$ = __________ lb/lb feed

16. Identify the total excess air rate for the system (i.e., to be maintained in the afterburner).

EA = _________ %

17. Calculate the additional nitrogen and oxygen present in the combustion gases due to excess air feed.

$$(O_2)_{EA} = EA \times \frac{(O_2)_{stoich(K)} + n_{AK}\,(O_2)_{stoich(A)}}{1 + n_{AK}} = \_\_\_\_\_\_\_\_\_ \text{ lb } O_2/\text{lb waste}$$

$$(N_2)_{EA} = 3.31\ \frac{\text{lb } N_2}{\text{lb } O_2}\ (\text{in air}) \times (O_2)_{EA} = \_\_\_\_\_\_\_\_\_ \text{ lb } N_2/\text{lb waste}$$

18. Calculate the total combustion gas flow.

Combustion gas flow = CG = CP + $(O_2)_{EA}$ + $(N_2)_{EA}$ = _________ lb/lb feed

19. Calculate the mass fraction of each combustion gas component.

CO_2: $\frac{CO_2}{CG}$ = _________ lb/lb gas

H_2O: $\frac{H_2O}{CG}$ = _________ lb/lb gas

N_2: $\frac{N_2(\text{from 15}) + (N_2)_{EA}}{CG}$ = _________ lb/lb gas

O_2: $\frac{(O_2)_{EA}}{CG}$ = _________ lb/lb gas

HCl: $\frac{HCl}{CG}$ = _________ lb/lb gas

HF: $\frac{HF}{CG}$ = _________ lb/lb gas

Br_2: $\frac{Br_2}{CG}$ = _________ lb/lb gas

I_2: $\frac{I_2}{CG}$ = _________ lb/lb gas

SO_2: $\frac{SO_2}{CG}$ = ________ lb/lb gas

P_2O_5: $\frac{P_2O_5}{CG}$ = ________ lb/lb gas

20. Identify those components that constitute less than 1-2% of the combustion gas. These components can be eliminated from further consideration in heat and material balance calculations. In most cases, CO_2, H_2O, N_2, and O_2 will be the only combustion gas components that need to be considered.

21. Calculate the volumetric flow of the major combustion products from the kiln at standard conditions of 68°F and 1 atm.

CO_2: $\left(\frac{CO_2}{CG}\right) \times CG \div 0.114$ lb/scf = ________ scf/lb

H_2O: $\left(\frac{H_2O}{CG}\right) \times CG \div 0.0467$ lb/scf = ________ scf/lb

N_2: $\left(\frac{N_2}{CG}\right) \times CG \div 0.0727$ lb/scf = ________ scf/lb

O_2: $\left(\frac{O_2}{CG}\right) \times CG \div 0.083$ lb/scf = ________ scf/lb

Other: $\left(\frac{\text{Other}}{CG}\right) \times CG \div (0.00259\ M)$ lb/scf = ________ scf/lb

where M = molecular weight

Total flow, $q = \sum$ = ________ scf/lb feed

$q \times (m_1 + m_2)(1 + n_{fK})(1 + n_{AK}) \div 60$ = ________ scfm

WORKSHEET 4-5. PROCEDURE TO CALCULATE EXCESS AIR RATE FOR A SPECIFIED TEMPERATURE AND FEED COMPOSITION

1. Identify the following input variables:

   From Worksheet 4-2, Step #5

   $(O_2)_{stoich}$ = __________ lb/lb feed

   From Worksheet 4-2, Step #6

   CO_2 = __________ lb/lb feed
   H_2O = __________ lb/lb feed
   N_2 = __________ lb/lb feed
   Other major component(s) = __________ lb/lb feed

   From Worksheet 4-3

   NHV_{waste} = __________ Btu/lb waste

   From proposed operating conditions

   Operating temperature, T = __________ °F
   Air preheat temperature, T_{air} (if applicable) = __________ °F

   If auxiliary fuel is to be burned in conjunction with the waste, also identify the following from Worksheet 4-2.

   n_f = __________ lb fuel/lb waste
   HV_f = __________ Btu/lb fuel

2. If air preheating is employed, calculate the corresponding enthalpy input to the incinerator. If the combustion air is not to be preheated, proceed to Step #3.

   $\Delta H_1' = 1.06(T_{air} - 77)(O_2)_{stoich}$
   = __________ Btu/lb feed

   $\Delta H_1 = \Delta H_1'(1 + EA)$

3. Calculate the heat generated by combustion of the waste or waste/auxiliary fuel mix.

   $$\Delta H_2 = \frac{NHV_{waste} + n_f\, HV_f}{1 + n_f}$$

   = __________ Btu/lb feed

4. Calculate the heat loss through the walls of the incinerator, assuming 5% loss.

$Q = 0.05\ \Delta H_2$

$=$ __________ Btu/lb feed

5. Calculate the enthalpy of the combustion products leaving the incinerator.

$0.26(CO_2 + N_2)(T - 77) =$ __________ Btu/lb feed

$0.49\ H_2O(T - 77) =$ __________ Btu/lb feed

Other x $\overline{C}_{p\ other}$ $(T - 77) =$ __________ Btu/lb feed

$\Delta H_3 = \sum =$ __________ Btu/lb feed

6. Calculate the enthalpy of excess air leaving the incinerator.

$\Delta H_4' = 1.1(T - 77)(O_2)_{stoich}$

$=$ __________ Btu/lb feed

$\Delta H_4 = \Delta H_4' \times EA$

7. Calculate the excess air percentage as follows:

$$EA = 100\left(\frac{\Delta H_1' + \Delta H_2 - Q - \Delta H_3}{\Delta H_4' - \Delta H_1'}\right)$$

$=$ _________ %

WORKSHEET 4-6. PROCEDURE TO ESTIMATE THE MAXIMUM ACHIEVABLE GAS RESIDENCE TIME AFTER THE DESIRED OPERATING TEMPERATURE HAS BEEN ACHIEVED

1. Identify the following input variables:

Volume of the incinerator chamber, V = __________ ft^3

Combustion gas flow rate, q = __________ scfm

Operating temperature, T = __________ °F

Combustion gas static pressure, P = __________ atm

2. Calculate the gas flow in actual cubic feet per second at operating temperature.

$$q' = \frac{q}{60P}\left(\frac{T + 460}{528}\right)$$

= __________ acf/s

3. Calculate the maximum achievable gas residence time in the incinerator after the desired operating temperature has been achieved.

$$\theta_{max} = \frac{V}{q'}$$

= __________ s

WORKSHEET 4-7. PROCEDURE TO CALCULATE SUPERFICIAL GAS VELOCITY AT OPERATING TEMPERATURE

Identify the following input variables:

Gas flow rate at operating temperature, q' = __________ acf/s
(See Worksheet 4-6)

Cross-sectional area of the incinerator chamber, A = __________ ft^2

Calculate:

Superficial gas velocity, v = q'/A

= __________ ft/s

WORKSHEET 4-8. PROCEDURE TO CALCULATE THE MAXIMUM ACHIEVABLE EXCESS AIR RATE FOR A ROTARY KILN OPERATING AT A SPECIFIED TEMPERATURE WITH A SPECIFIED FEED COMPOSITION

1. Identify the following input variables:

From Worksheet 4-4, Step 6

$(O_2)_{stoich(K)}$ = __________ lb O_2/lb kiln feed

From Worksheet 4-4, Step 7

$CO_{2(K)}$ = __________ lb/lb feed

$H_2O_{(K)}$ = __________ lb/lb feed

$N_{2(K)}$ = __________ lb/lb feed

Other major combustion product(s) = __________ lb/lb feed

From Worksheet 4-4, Step 2

Liquid waste feed fraction, n_1 = __________ lb liquid/lb waste
Solid waste feed fraction, n_2 = __________ lb solid/lb waste

From Worksheet 4-3

Liquid waste heating value, NHV_1 = __________ Btu/lb
Solid waste heating value, NHV_2 = __________ Btu/lb

From proposed operating conditions

Kiln operating temperature, T_K = __________ °F
Air preheat temperature, T_{air} = __________ °F
(if applicable)

If auxiliary fuel is to be burned in the kiln along with the wastes during normal operation, identify the following from Worksheet 4-4:

n_{fK} = __________ lb fuel/lb waste
HV_{fK} = __________ Btu/lb fuel

2. If air preheating is employed, calculate the corresponding enthalpy input to the kiln. If the combustion air is not preheated, proceed to Step 3:

$$\Delta H_1'{}_{(K)} = 1.06\ (T_{air} - 77)(O_2)_{stoich(K)} = \underline{\hspace{3cm}}\ \text{Btu/lb feed}$$

$$\Delta H_{1(K)} = \Delta H_1'{}_{(K)}\ (1 + EA_K)$$

3. Calculate the maximum heat generated in the kiln by combustion of the wastes or waste/auxiliary fuel mix:

$$\Delta H_2 = \frac{n_1 NHV_1 + n_2 NHV_2 + n_{fK} HV_{fK}}{1 + n_{fK}} = \underline{\hspace{3cm}}\ \text{Btu/lb feed}$$

4. Estimate the heat loss through the walls of the kiln, assuming 5% loss:

$$Q_{(K)} = 0.05\ \Delta H_{2(K)} = \underline{\hspace{3cm}}\ \text{Btu/lb feed}$$

5. Calculate the enthalpy of the combustion products leaving the kiln:

$$0.26\left(CO_{2(K)} + N_{2(K)}\right)(T_K - 77) = \underline{\hspace{3cm}}\ \text{Btu/lb feed}$$

$$0.49\ H_2O_{(K)}\ (T_K - 77) = \underline{\hspace{3cm}}\ \text{Btu/lb feed}$$

$$\text{Other}_K\left(\frac{\text{lb}}{\text{lb feed}}\right) \times \overline{C_p}\ \text{other}\ (T_K - 77) = \underline{\hspace{3cm}}\ \text{Btu/lb feed}$$

$$\Delta H_{3(K)} = \quad = \underline{\hspace{3cm}}\ \text{Btu/lb feed}$$

6. Calculate the enthalpy of excess air levaing the kiln:

$$\Delta H_4'{}_{(K)} = 1.1\ (T_K - 77)\ (O_2)_{stoich(K)} = \underline{\hspace{3cm}}\ \text{Btu/lb feed}$$

$$\Delta H_{4(K)} = \Delta H_4'{}_{(K)}\ EA_K$$

7. Calculate the excess air percentage as follows:

$$EA_K = 100\left(\frac{\Delta H_1'{}_{(K)} + \Delta H_{2(K)} - Q_K - \Delta H_{3(K)}}{\Delta H_4'{}_{(K)} - \Delta H_1'{}_{(K)}}\right) = \underline{\hspace{3cm}}\ \%$$

WORKSHEET 4-9. PROCEDURE TO CALCULATE EXCESS AIR IN A ROTARY KILN AFTERBURNER FOR A SPECIFIED AFTERBURNER TEMPERATURE AND OVERALL FEED COMPOSITION

1. Identify the following input variables:

From Worksheet 4-4, Steps 6 and 12

$(O_2)_{stoich(K)}$ = ________ lb O_2/lb kiln feed

$(O_2)_{stoich(A)}$ = ________ lb O_2/lb afterburner feed

From Worksheet 4-4, Step 15

CO_2 = ________ lb/lb feed
H_2O = ________ lb/lb feed
N_2 = ________ lb/lb feed
Other major combustion product(s) = ________ lb/lb feed

From Worksheet 4-4, Step 14

Afterburner/kiln feed ratio, n_{AK} = _____ lb afterburner feed/lb kiln feed

From Worksheet 4-3

Afterburner waste heating value, NHV_3 = ________ Btu/lb

From proposed operating conditions

Afterburner temperature, T_A = ________ °F
Air preheat temperature, T_{air} = ________ °F
(if applicable)

If auxiliary fuel is to be burned in the afterburner along with liquid wastes during normal operation, identify the following from Worksheet 4-4:

n_{fA} = ________ lb fuel/lb afterburner waste feed
HV_{fA} = ________ Btu/lb fuel

From Worksheet 4-8,

$\Delta H_{2(K)}$ = ________ Btu/lb kiln feed

2. If air preheating is employed, calculate the corresponding enthalpy input to the kiln and afterburner combined. If the combustion air is not preheated, proceed to Step 3:

$$\Delta H_1' = 1.06\,(T_{air} - 77)\left[(O_2)_{stoich(K)} + (O_2)_{stoich(A)}\right] = \_\_\_\_ \text{ Btu/lb feed}$$

$$\Delta H_1 = \Delta H_1'\,(1 + EA)$$

3. Calculate the heat generated in the kiln and afterburner by combustion of the total waste/auxiliary fuel feed:

$$\Delta H_{2(A)} = \frac{NHV_3 + n_{fA}HV_{fA}}{1 + n_{fA}} = \_\_\_\_\_\_\_\_ \text{ Btu/lb afterburner feed}$$

$$\Delta H_2 = \frac{\Delta H_{2(K)} + n_{AK}\Delta H_{2(A)}}{1 + n_{AK}} = \_\_\_\_\_\_\_\_ \text{ Btu/lb feed}$$

4. Estimate the heat loss through the walls of the kiln and afterburner, assuming 5% loss:

$$Q = 0.05\,\Delta H_2 = \_\_\_\_\_\_\_\_ \text{ Btu/lb feed}$$

5. Calculate the enthalpy of the combustion products leaving the afterburner:

$$0.26\,(CO_2 + N_2)\,(T_A - 77) = \_\_\_\_\_\_\_\_ \text{ Btu/lb feed}$$

$$0.49\,H_2O\,(T_A - 77) = \_\_\_\_\_\_\_\_ \text{ Btu/lb feed}$$

$$\text{Other}\left(\frac{\text{lb}}{\text{lb feed}}\right) \times \overline{C}_{p\ \text{other}}\,(T_A - 77) = \_\_\_\_\_\_\_\_ \text{ Btu/lb feed}$$

$$\Delta H_3 = \sum = \_\_\_\_\_\_\_\_ \text{ Btu/lb feed}$$

6. Calculate the enthalpy of excess air leaving the afterburner:

$$\Delta H_4' = 1.1\,(T_A - 77)\left[(O_2)_{stoich(K)} + (O_2)_{stoich(A)}\right] = \_\_\_\_\_\_ \text{ Btu/lb feed}$$

$$\Delta H_4 = \Delta H_4'\,EA$$

7. Calculate the excess air percentage in the afterburner:

$$EA = 100\left(\frac{\Delta H_1' + \Delta H_2 - Q - \Delta H_3}{\Delta H_4' - \Delta H_1'}\right) = \_\_\_\_\_\_\_\_ \%$$

WORKSHEET 4-10. PROCEDURE TO ESTIMATE SOLID WASTE RETENTION TIMES IN ROTARY KILNS

Identify the following input variables:

Kiln length, L = __________ ft
Kiln diameter, D = __________ ft
Slope of kiln, S = __________ ft/ft
Rotation velocity, N = __________ rpm

Calculation:

$\theta_s = 0.19 \, (L/D)/SN =$ __________ min

WORKSHEET 4-11. PROCEDURE TO CALCULATE AUXILIARY FUEL CAPACITY REQUIREMENTS FOR STARTUP AT DESIGN AIR FLOW FOR WASTE COMBUSTION

1. Identify the following input data from the proposed operating conditions, Section 4.3.2, and/or Section 4.3.3.

   Auxiliary fuel type: ______________________________

   Fuel heating value, NHV = ______________________ Btu/lb

   Desired operating temperature, T_{out} = ______________________ °F

   Average proposed waste feed rate, m_w = ______________________ lb/hr

   Stoichiometric oxygen requirement for waste, $(O_2)_{stoich(w)}$ = ______________________ lb O_2/lb waste

   Proposed excess air rate, EA = ______________________ %/100

2. Identify the stoichiometric oxygen requirements and combustion product yields for the auxiliary fuel from the following table.

Fuel	$(O_2)_{stoich(f)}$, lb/lb fuel	Combustion products yields, lb/lb fuel CO_2	H_2O	N_2
Residual fuel oil (e.g., No. 6)	3.16	3.18	0.92	10.5
Distillate fuel oil (e.g., No. 2)	3.32	3.20	1.11	11.0
Natural gas	3.67	2.54	2.04	12.2

3. Calculate the enthalpy of the fuel combustion gases.

$$h_i = \Sigma\, n_{if}\, \overline{C_{pi}}\, (T_{out} - 77)$$
$$= \left[0.26(CO_2 + N_2) + 0.49\, H_2O\right]\, (T_{out} - 77)$$

   = ______________________ Btu/lb fuel

4. Calculate the heat output from the unit associated with design air flow for waste combustion.

$$Q_1 = 1.12\, m_w\, (O_2)_{stoich(w)}\, (1 + EA)\, (T_{out} - 77)$$

   = ______________________ Btu/hr

5. Calculate "enthalpy" of air consumed in fuel combustion.

$h_2 = 1.12\ (O_2)_{stoich(f)}\ (T_{out} - 77)$

$=$ ______________________ Btu/lb fuel

6. Calculate the heat of fuel combustion, less 5% heat loss through the refractory walls.

$h_3 = 0.95\ NHV_f =$ ____________________ Btu/lb fuel

7. Calculate the required auxiliary fuel capacity.

$m_f = \frac{Q_1}{h_3 + h_2 - h_1} =$ ___________________ lb fuel/hr

8. If necessary for comparison with the reported auxiliary fuel rating, calculate the required auxiliary fuel capacity in Btu/hr.

$Q_f = m_f\ NHV_f =$ _______________________ Btu/hr

WORKSHEET 4-12. PROCEDURE TO ESTIMATE PARTICULATE CONCENTRATION AND EMISSION RATE FROM LIQUID INJECTION INCINERATORS

1. Identify the following input data:

   Ash content of waste, ASH = ______________________________ wt%

   Average waste feed rate, m_w = ____________________________ lb/hr

   Volumetric combustion gas flow rate, q = ____________________ scfm

   Volumetric fraction of oxygen in the gas, $(O_2)_v$ = ________________

2. Calculate the particulate emission rate, based on the ash content of the waste

   $m_p = ASH \times m_w =$ ____________________________ lb/hr

3. Correct the volumetric combustion gas flow rate to zero percent excess air.

   $q_a = q \left[1 - 4.77(O_2)_v \right] =$ __________________________ scfm

4. Calculate the particulate loading in the gas at zero percent excess air.

   $c_p = 117 \dfrac{m_p}{q_a} =$ __________________ gr/scf

WORKSHEET 4-13. INTERNAL CONSISTENCY CHECK FOR PROPOSED CONDITIONS OF GAS VELOCITY, LIQUID TO GAS RATIO, AND PRESSURE DROP FOR VENTURI SCRUBBERS

1. Identify the following input data:

Proposed liquid to gas ratio, $\frac{Q_L}{Q_G}$ = ____________________ gal/1,000 ft^3

Proposed gas velocity (at the throat), U_G = ____________________ ft/s

Cross-sectional throat area, A = ____________________ ft^2

Gas density (downstream of throat), ρ_a = ____________________ lb/ft^3

ρ_a may be estimated from the ideal gas law:

$$\rho_a = \frac{M\ P}{RT}$$

where M = average molecular weight of gas (normally about 30)
P = absolute pressure (atm)
R = gas constant = 0.73 atm $ft^3/°R$ lb mol
T = absolute temperature (°R)

2. Calculate the pressure drop, ΔP

$$\Delta P = \frac{(U_G)^2\ \rho_a A^{0.133}}{1270}\left(\frac{Q_L}{Q_G}\right)^{0.78} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_ \text{ in. WG}$$

WORKSHEET 4-14. PROCEDURE TO CALCULATE THE NUMBER OF PLATES REQUIRED FOR A SPECIFIED GASEOUS POLLUTANT REMOVAL EFFICIENCY[a]

1. Identify the desired removal efficiency for pollutant i.

   E_i = ____________________ %/100

2. From Table 4-19 or other sources, identify the average Murphree vapor phase efficiency for the plate tower

   E_{MV} = ________________________ %/100

3. Calculate the required number of plates

$$N_\rho = \frac{\ln (1 - E_i)}{\ln (1 - E_{MV})} = \rule{6cm}{0.4pt}$$

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[a] This procedure is only applicable for gaseous pollutants that are highly soluble or chemically reactive with the scrubbing liquid.

WORKSHEET 4-15. PROCEDURE TO CALCULATE THE MAXIMUM LIQUID TO GAS RATIO FOR PLATE TOWERS

1. Identify the inlet temperature to the tower and the tower diameter.

T = __________ °F + 460 = __________ °R

d = __________ ft

2. Identify the volumetric fraction of each major component in the gas.

Y_{CO_2} = ____________________

Y_{H_2O} = ____________________

Y_{N_2} = ____________________

Y_{O_2} = ____________________

Y_{other} = ____________________

3. Calculate the average molecular weight of the gas

$$\bar{M} = 44Y_{CO_2} + 18Y_{H_2O} + 28Y_{N_2} + 32Y_{O_2} + M_{other}\,Y_{other}$$

= ____________________ lb/lb mol

4. Calculate the gas density

$$\rho_G = 1.37\,\frac{\bar{M}}{T(°R)} = \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\ \text{lb/ft}^3$$

5. Determine the scrubber liquor density

ρ_L = ____________________ lb/ft^3

6. Determine the Souders-Brown constant, K, from Reference 6 or other sources. (For 24-in. tray spacing, use K = 0.17)

7. Calculate the maximum liquid-to-gas ratio

$$\left(\frac{Q_L}{Q_G}\right)_{max} = \frac{630}{Kd}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{0.5} = \underline{\hspace{5cm}} \text{ gal/1,000 ft}^3$$

WORKSHEET 4-16. PROCEDURE TO CALCULATE PRESSURE DROP BETWEEN THE INCINERATOR AND INDUCED DRAFT FAN

1. Identify and/or calculate the following input data relevant to the combustion gas:

   a) From Section 4.3.2,

   Approximate waste feed rate, m = __________ lb/hr
   Combustion gas mass flow, CG = __________ lb/lb waste
   CG x m = __________ lb/hr
   Combustion gas volumetric flow, q_{std} = __________ scfm

   Volumetric fraction of each major component in the gas

   y_{CO_2} = __________

   y_{H_2O} = __________

   y_{N_2} = __________

   y_{O_2} = __________

   y_{other} = __________

   b) Calculate the average molecular weight of the gas

   $$\bar{M} = 44\ y_{CO_2} + 18\ y_{H_2O} + 28\ y_{N_2} + 32\ y_{O_2} + M_{other}\ y_{other}$$

   = __________ lb/lb mol

2. Calculate the actual gas flow rate and gas density at the entrance to each gas conditioning or air pollution control device and the fan using the following equations:

$$q = q_{std}\left(\frac{T°F + 460}{528}\right),\ \text{acfm}$$

$$\rho_{gas} = 1.37\left(\frac{\bar{M}}{T°F + 460}\right),\ \text{lb/ft}^3$$

Location (inlet)	q, acfm	ρ_{gas}, lb/ft^3
Quench tower		
Scrubber		
Demister		
Fan		
Other (specify) ________		

Approximate gas temperatures at these locations need to be determined.

3. From manufacturer specifications, estimate the pressure drop across each gas conditioning device for the gas flow rates calculated in the preceding step.

Location	ΔP, in. H_2O
Quench tower	
Scrubber	
Demister	
Other (specify) ________	________
TOTAL	

4. For the segments of ductwork entering the aforementioned devices, determine the inner diameter (D), the cross-sectional area of the duct (A_d), the cross-sectional area of the device preceding the duct (A_p), the length of straight duct (L_s), the radius of curvature of any bends in the duct (R), and the gas velocity through the duct.

If the duct is square, use the length of a side as the equivalent diameter. If the duct is rectangular, calculate an equivalent diameter by the following equation:

$$D = \frac{2\,ab}{a + b},$$ where a and b are width and depth of the duct.

Figure 4-15 in Section 4.4.4 shows how radii of curvature can be estimated.

Gas velocities can be calculated by the following equation:

$$V = \frac{q}{60A_d},\ \text{ft/s}$$

Location (inlet duct)	D, in.	A_d, ft^2	A_p, ft^2	A_d/A_p	L_s, ft	R, in.	V, ft/s
Quench tower							
Scrubber							
Demister							
Fan							
Other (specify) ________							

5. Calculate the pressure drop across each straight length of ductwork using Figure 4-13 in Section 4.4.4. and the known diameters of the ducts, combustion gas mass flow rate, average molecular weight of the gas, and temperatures at the specified locations.

Figure 4-13 yields pressure drop values per length of straight duct. These can be converted to total pressure drops by the following calculation:

$$\Delta P = \left(\frac{\Delta P}{L}\right) L_s, \text{ in } H_2O$$

Location (inlet duct)	ΔP, in. H_2O
Quench tower	
Scrubber	
Demister	
Fan	
Other (specify) ________	________

6. Estimate the pressure drop across any bends in the ductwork.

Figure 4-14 in Section 4.4.4 shows L_e/D values as a function of R/D for 90° bends,

where L_e = equivalent length, in.
D = diameter, in.
R = radius of curvature, in.

L_e/D values can be converted to pressure drops by the following calculation:

$$\Delta P' = \Delta P \left(\frac{L_e}{D}\right)\left(\frac{12D}{L_s}\right), \text{ in. } H_2O$$

where $\Delta P'$ = pressure drop across the bend in the duct, in. H_2O

For 45° bends, $\Delta P'$ is about 65% of that calculated for a 90° bend. For 180° bends, $\Delta P'$ is about 140% of that calculated for a 90° bend. Thus,

$$\Delta P'_{(45°)} = 0.65\ \Delta P'_{(90°)}$$

$$\Delta P'_{(180°)} = 1.4\ \Delta P'_{(90°)}$$

Location (inlet duct	$\Delta P'$, in. H_2O
Quench tower	
Scrubber	
Demister	
Fan	
Other (specify) __________	____________
TOTAL	

7. Estimate the additional pressure drops due to sudden contraction of flow at the entrance to each duct.

$$\Delta P' = .003\ K_c\ \rho_{gas}\ V^2,\ \text{in. } H_2O$$

where $\Delta P''$ = pressure drop due to contraction, in H_2O

ρ_{gas} = gas density, lb/ft^3

V = gas velocity, ft/s

K_c = sudden contraction-loss coefficient

K_c is a function of the ratio of the duct cross-sectional to the cross-sectional area of the preceding vessel, A_d/A_p. Table 4-21 in Section 4.4.4 shows this relationship.

Location (inlet duct)	$\Delta P''$, in. H_2O
Quench tower	
Scrubber	
Demister	
Fan	
Other (specify) __________	____________
TOTAL	

8. Calculate the total pressure drop across the system by summing the totals from Steps 3, 5, 6, and 7

ΔP_{total} = __________ in. H_2O

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CHAPTER 5

OVERALL FACILITY DESIGN, OPERATION, AND MONITORING

5.1 INTRODUCTION

Incineration is one controlled combustion process used in the ultimate disposal of unusable hazardous wastes that result from industrial and chemical manufacture. Careful selection of equipment and processes for the incineration of chemical wastes is essential to ensure that the basic obligations of safe handling and proper ultimate disposal are met in a satisfactory manner. In addition to fulfilling social obligations, an effective system will satisfy regulatory needs with minimum, adverse community reaction.

Prior to incineration, the handling, storage, and feeding of hazardous wastes require special care to ensure safety and reduce exposure. During incineration and while the facility operates, certain parameters must be monitored by the operators to assure that proper conditions are maintained in day-to-day operation.

Although the problems are substantially reduced, incineration of hazardous waste materials alone does not eliminate all of the disposal problems associated with hazardous waste. Most incinerators produce combustion products that must be properly removed prior to discharging gas products to the environment. These products include ash or inert residues from such things as silica oxides and/or metals. Captured gas products, such as HCl, when reacted with caustic solutions in the scrubber, can also produce dissolved and suspended solids. These solutions from the quench process and scrubber reactions must be carefully disposed of to ensure the entire sequence of combustion is safe. Whenever these wastes are of a nonhazardous nature, standard procedures can be used for their treatment and ultimate disposal. However, in some cases the secondary wastes can be hazardous themselves and require special handling.

5.1.1 Purpose

The purpose of this chapter is to provide the permit writer with engineering back-up information to supplement the guidance criteria necessary to judge the capability of the overall incineration facility to technically and practically process and monitor hazardous wastes safely and effectively.

This chapter discusses overall facility layouts, requirements common to all facilities, site and combustor specific requirements, material and process flows, waste receiving procedures, waste and other storage, material handling equipment, emergency and safety procedures and provisions, personnel safety, monitoring for the incineration process itself, monitoring of the air pollution control system, monitoring of waste handling and treatment systems, monitoring and controlling parts of the overall facility that may become fugitive emission sources, proper handling and disposal of quench/scrubber water and ash, and sampling and analysis of wastewaters and ash.

5.1.2 Hazardous Waste Incinerator Facility Design

The overall facility design of hazardous waste incinerators is significantly influenced by the category of waste involved; i.e., solids, liquids, or sludges. The systematic approach to facility design, therefore, requires investigation of the composition of each class of waste to define the equipment and operating procedures for each of the following elements:

1. Safety (toxicity, fire explosion)
2. Transportation and unloading
3. Segregation of wastes during storage
4. Storage
5. Handling and feeding
6. Monitoring
7. Fugitive emission control
8. Scrubber/quench water treatment
9. Residue handling and disposal
10. Secondary problems (e.g., stream pollution, runoff, ground-water contamination).

The overall success of an incinerator facility depends upon the successful integration of storage, feeding, and firing equipment; often these are areas which do not receive as much attention as is necessary. In the case of hazardous waste incineration it is crucial that these areas require special attention.

Figure 5-1 is a block diagram of a typical incinerator facility layout. In an overall facility evaluation, the key areas are the facilities and equipment before and after the combustor; i.e., waste receiving, waste storage, waste blending, transfer between these areas, equipment feeding waste to the incinerator, handling and treatment of quench and scrubber waters, and ash disposal. Figure 5-2 is a schematic diagram of an incinerator facility handling both solid and liquid wastes; illustrating the interrelationships between the key facility areas.

5.2 INCINERATOR FACILITY SITE SELECTION AND OPERATION

5.2.1 Site Selection Concerns

The Guidance Manual for Location Standards contains guidance for complying with general (i.e., applicable to all facilities) location standards ¶264.18. Flood plains, holocene faults, and endangered and threatened species are discussed.

The selection of a site for a hazardous waste incineration facility is a phased decision process which has occurred prior to making a permit application. Site screening is the process of identifying and evaluating a parcel of land for its suitability as a hazardous waste disposal site. Specific site-screening criteria which the permit applicant has addressed include geologic,

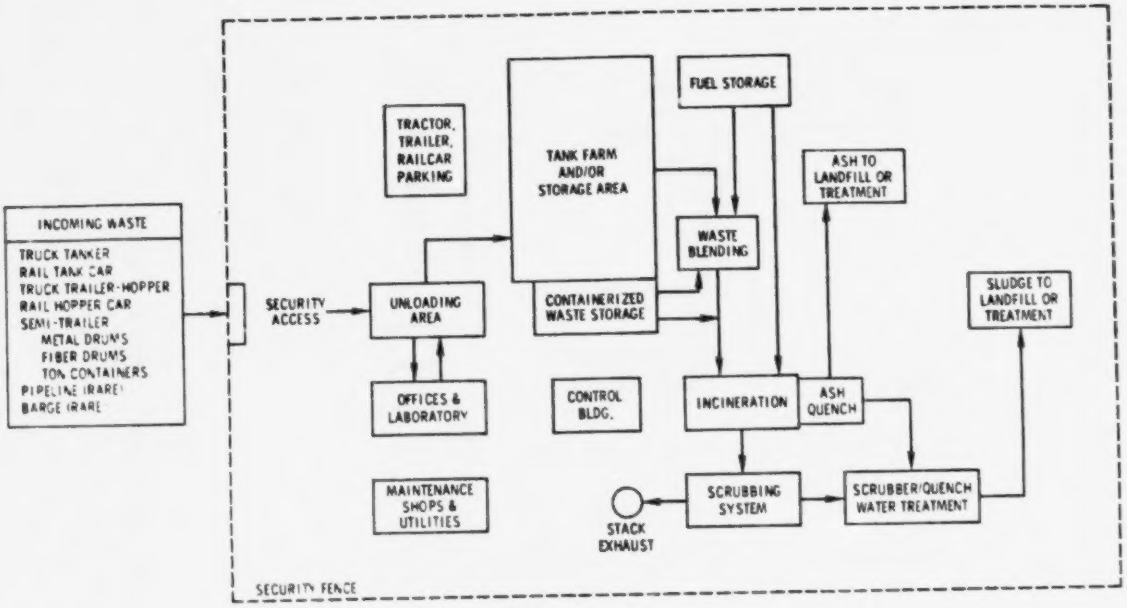
INCOMING WASTE
TRUCK TANKER
RAIL TANK CAR
TRUCK TRAILER-HOPPER
RAIL HOPPER CAR
SEMI-TRAILER
METAL DRUMS
FIBER DRUMS
TON CONTAINERS
PIPELINE (RARE)
BARGE (RARE)
SECURITY ACCESS
TRACTOR, TRAILER, RAILCAR PARKING
TANK FARM AND/OR STORAGE AREA
FUEL STORAGE
ASH TO LANDFILL OR TREATMENT
WASTE BLENDING
UNLOADING AREA
CONTAINERIZED WASTE STORAGE
SLUDGE TO LANDFILL OR TREATMENT
OFFICES & LABORATORY
CONTROL BLDG.
INCINERATION
ASH QUENCH
MAINTENANCE SHOPS & UTILITIES
STACK EXHAUST
SCRUBBING SYSTEM
SCRUBBER/QUENCH WATER TREATMENT
SECURITY FENCE

Figure 5-1. Typical incinerator facility layout.

hydrogeologic, topographic, economic, social, and political aspects. While many sites may exist which meet technical, economic, and ecological criteria, public acceptance or rejection may ultimately decide the fate of the facility [1].

The main geological constraints that can render a site unsuitable for a hazardous waste incinerator facility are historical or predicted seismic activity, landslide potential, soil slump of solifluction, and volcanic or hot spring activities.

The main topographic constraints are susceptibility to flooding, erosion, and offsite drainage runoff. The site will need sufficient area for the construction of a runoff-holding pond (or diversion to an existing holding pond) to retain surface runoff which may contain hazardous substances in solution. Because of the holding pond and flood protection criteria, siting in flood plains is not normally acceptable.

The primary climatic features which can adversely affect an incineration site are the amount of annual or seasonal precipitation and incidence of severe storms. Copious precipitation will cause surface runoff and water infiltration through the soil. Runoff, that amount of rainfall that does not infiltrate the soil, depends on such factors as the intensity and duration of the precipitation, the soil moisture content, vegetation cover, permeability of the soil, and slope of the site. Normally, the runoff from a 10-year storm (recurrence interval of only once in 10 years) or annual spring thaw, whichever is greater, is containable by the site's natural topography. If not, berms, dikes, and other runoff control measures must be constructed to modify the site.

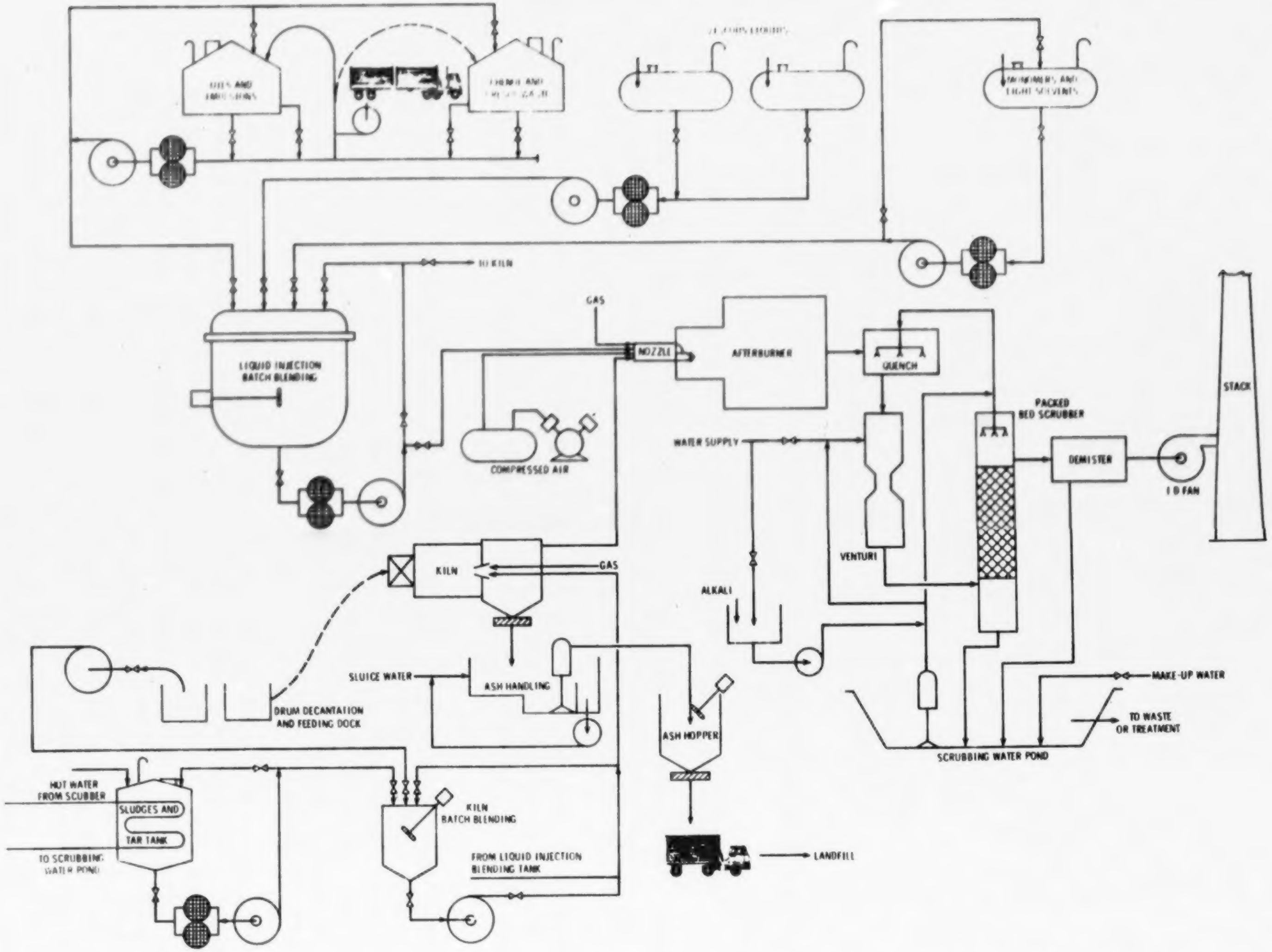
OILS AND EMULSIONS
AQUEOUS LIQUIDS
MONOMERS AND LIGHT SOLVENTS
TO KILN
LIQUID INJECTION BATCH BLENDING
GAS
NOZZLE
AFTERBURNER
QUENCH
COMPRESSED AIR
WATER SUPPLY
PACKED BED SCRUBBER
DEMISTER
I D FAN
STACK
VENTURI
ALKALI
KILN
GAS
SLUICE WATER
ASH HANDLING
DRUM DECANTATION AND FEEDING DOCK
ASH HOPPER
MAKE-UP WATER
TO WASTE OR TREATMENT
SCRUBBING WATER POND
HOT WATER FROM SCUBBER
SLUDGES AND
TAR TANK
TO SCRUBBING WATER POND
KILN BATCH BLENDING
FROM LIQUID INJECTION BLENDING TANK
LANDFILL

Figure 5-2. Typical incinerator facility flow diagram, solid and liquid wastes.

Ecological site features are those elements determined through earlier studies and environmental impact statements (EIS) which determine whether ecosystems at the site are in a delicate balance. Whether a site is a habitat for rare and endangered species; or used seasonally by migratory wildlife is also a factor determined for final site selection.

Cultural site features are those elements that are a direct result of human activities which modify and affect the site's desirability as a hazardous waste incineration facility--access, land-use, and aesthetics. Land areas zoned for nonresidential uses and adequate buffer zones are generally preferred for siting a hazardous waste management facility. The site ideally needs to contain sufficient land area to provide a concentric ring of unoccupied space as a buffer zone between active storage, treatment, and disposal areas, and the nearest area of human activity. Vegetation, topography, distance, and artificial barriers are all potential means to screen facility activities from line-of-sight observations from commercial, residential, or recreational areas.

One of the most difficult problems faced by a hazardous waste incineration facility applicant has been that of gaining public approval from a community for construction of the facility. No matter how thoroughly the above parameters have been examined in the facility site selection, public acceptance or rejection probably decides the fate of the facility. Public awareness of the planned facility, early planning input, and active participation by political leaders, public officials, environmental groups, as well as other public interest groups and adjacent industry have led to successful facility sitings in the past.

5.2.2 Operation of the Facility

Preplanning of the proper operation of a hazardous waste incineration facility is necessary to protect and prevent adverse effects of the facility on the public health or to the environment. Proper facility operation, on a day-to-day basis, includes plans and manuals of operation for handling wastes, safety at the site, monitoring of operating parameters, monitoring to assure protection of the environment, and operator training. These plans are developed within the operating company (and corporate structure) and are done in cooperation with other neighboring or similar organizations and with governmental agencies. It may not always be possible for all of them to fully cooperate or participate, but through planned action each organization is made aware of certain available assistances.

5.2.2.1 Operations Plan--

An operations plan includes the following:

(1) Classification of wastes to be handled and estimated quantities

(2) Methods and processes utilized

  (a) Facility capacity
  (b) Detailed description of each process

(3) Storage and disposal procedures

    (a) Plans for receipt, checking, processing, segregating incompatible wastes, and odor control
    (b) Life of facility based on projected use

(4) Monitoring Procedures

    (a) Monitoring of incinerator operating parameters
    (b) Monitoring and recording of incoming wastes
    (c) Leachate control and groundwater monitoring
    (d) Security system
    (e) System for monitoring water and air pollution affecting area outside the site
    (f) Air pollution control device monitoring

(5) Administrative Procedures

    (a) Hours of operation/day and days/week
    (b) Security procedures including entry control, hours manned, lighting, and other procedures to prevent unauthorized entry
    (c) Procedures planned and equipment available in case of breakdowns, inclement weather, or other abnormal conditions.
    (d) Description of recordkeeping procedures, types of records to be kept, and use of records by management to control the operation.
    (e) List of general qualifications of key operating personnel
    (f) Maintenance and inspection schedules

5.2.2.2 Operations Manual--

Once in operation, the incinerator facility will maintain operation guides or manuals, covering the routine workings of the plant. An operations guide can include:

(1) A scaled engineering drawing, pictorial flow diagram, or scale model of the plant, showing all major components by name and function.
(2) A set of formal drawings at the plant for reference by operational and maintenance personnel
(3) Equipment manuals
(4) Equipment catalogs
(5) Spare parts lists
(6) Job or task functions for each assignment during a typical shift

5.2.2.3 Emergency Manual or Handbook--

An emergency manual or handbook is prepared which specifies the plan-of-action for any type of emergency the incinerator facility may reasonably expect to encounter. These include weather extremes (severe cold, heavy snowfall, hail damage, hurricances, tornadoes, high winds, or lightning damage), floods, earthquakes, power outages, bomb scares, fires and explosion, and spills (See Section 5.2.2.5). The typical remedial actions for emergency situations presented in Table 5-1 cover many of the items that can be included in the

TABLE 5-1. HAZARDOUS WASTE INCINERATOR MALFUNCTIONS AND REMEDIAL OR EMERGENCY RESPONSES

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
1	Partial or complete stoppage of liquid waste feed delivery to all liquid burners	L C	(a) Flowmeter reading out of specified range (b) Pressure build-up in feed lines (c) Change in combustion zone temperature (d) Feed pump failure, zero amps	Halt waste feed, start trouble-shooting and maintenance in affected system. Reinitiate or increase auxiliary fuel feed to maintain combustion zone temperatures; continue operation of air pollution control devices (APCD)
2	Partial or complete stoppage of liquid waste to only one burner	L C	As in (a), (b) and (c), above	Halt waste feed to affected burner only
3	Partial or complete stoppage of solid wastes feed to rotary kiln	RK C	(a) Drop in RK combustion temperature (b) Power loss in waste feed conveyor or other feed system	As in 1, above
4	"Puffing", or sudden occurrence of fugitive emissions from RK due to thermal instability or excessive feed rate of wastes to RD, or failure of seals	RK C	(a) Pressure surge in kiln (rapid change in manometer level) (b) Visible emission from air seals at either end of kiln	(a) Halt feeding of any solid waste to kiln for 10-30 min, but continue combustion (b) Evacuate unneeded personnel from immediate vicinity of kiln (c) Reevaluate waste prior to further incineration

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
5	Failure of forced air supply to liquid waste feed or fuel burners	L RK C	(a) Flowmeter reading for air supply off scale (b) Automatic flame detector alarm activated (c) Zero amps or excessive current draw on blower motor(s)	(a) Halt waste and fuel feed immediately (b) Start trouble shooting immediately and restart as soon as possible (c) Continue operation of APCD's but reduce air flow at induced draft fan by "damping" accessory
6	Combustion temperature too high	L RK C	(a) Temperature indicator(s) at instrument control panel (b) Annunciator or other alarm sounded	(a) Check fuel or waste feed flow rates; reduce if necessary (b) Check temperature sensors (c) Check other indicators in combustor, if multiple sensors used (d) Automatic or manual activation of combustion chamber vent (sometimes called an "emergency stack cap")

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
7	Combustion temperature too low	L RK C	(a) - as above (b) - as above	(a) Check other indicators in combustor, if multiple sensors are used (b) Check fuel or waste feed flow rates; increase if necessary (c) Check sensor accuracy
8	Sudden loss of integrity of refractory lining	L RK C	(a) Sudden loud noise (b) Partial stoppage of air drawn into combustor, resulting in decreasing combustion temperatures, increased particulate emissions, and development of hot spots on external of combustor shell	Shut down facility as quickly as possible
9	Excess opacity of stack plume	L RK C	Visual, or instrument opacity readings which are above maximum allowable operating point	(a) Check combustion conconditions, especially temperatures O_2 (excess air) and CO monitor (b) Check APCD operation (c) Check nature and feed rates of wastes being burned (d) Check ESP rapping interval, cycle duration and intensity

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
10	CO in exhaust gas in excess of 100 ppm, or in excess of normal CO values	L	CO indicator	Check and adjust combustion conditions, especially temperature and excess air (O_2 in stack gas), and adjust accordingly
11	Indication of or actual failure of Induced Draft Fan	L RK C	(a) Motor overheating (b) Excessive or zero current (amps) (c) Total stoppage of fan (d) Δp drop across blower inlet and outlet	(a) Switch to standby fan, if available (b) If two induced draft fans are used in series, reduce operational levels immediately, stop the failing unit, and operate at reduced rate on one fan only, until maintenance can be completed (c) If there is only one fan, and the fan failure appears serious, shift into an emergency shutdown mode for entire incinerator

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
12	Increase in gas temperature after quench zone, affecting scrubber operation	L RK C	(a) Partial or total loss of water supply to quench zone (b) Increase of combustion temperatures	(a) Check water flow to quench zone. Prepare for limited operation rate until water supply is restored (b) Check combustion conditions, especially temperature
13	Partial or complete stoppage of water or caustic solution to scrubber(s)	L RK	(a) Decrease in Δp across scrubber, as indicated by manometers, or other instruments (b) Zero or increased amps on water or solution pumps (c) Flowmeter readings out of specified range (d) Large increase in acid components in stack gas as detected by NDIR or other type instruments	(a) Halt waste feed, start troubleshooting and maintenance in affected system (b) Start up redundant pumps, if available (c) Check recycle water or solution tank levels (d) If using alkaline solution, switch to water supply if available (e) Check for deposition of solids from recycled liquors in pump lines (f) Use emergency (standby) water supply which will feed water by gravity until the whole system can be shutdown

TABLE 5-1 (continued)

No.	Malfunction	Type incinerator[a]	Malfunction indication	Response
14	Deposition of solids in scrubber from recycled wastes or caustic solution, or from excess solids emissions from combustor	L RK C	(a) Buildup of Δp across scrubber as indicated by manometers or other instruments. (b) Increased hold-up of liquor in packed or tray towers, up to and including flooded condition. This can also be detected by liquid level indicators.	This requires a shutdown to clean out the tower and internals. The shutdown can be scheduled if the deposit buildup is gradual and is monitored.
15	pH of recycled scrubber liquor not in spec	L RK C	(a) Continuous, or spot-checking pH indicator shows actual pH to be outside of desired operating range (d) Drop in scrubber efficiency with excess acid gas in stack gas	(a) Check for adequate supply and metering of alkaline agent (b) Check accuracy of pH meter and alkaline solution metering pump associated with recycling of scrubber liquor
16	Failure of demister operation	L RK C	Increased Δp, as measured by manometer, due to solids accumulation in demister element	Back-wash element

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[a]. L = Liquid injection; RK = Rotary kiln; C = Combination liquid injection and rotary kiln.

emergency handbook, but other items may be needed as dictated by the anticipated emergencies and the available resources.

5.2.2.4 Leak Detection and Repair Plan--

Any facility that processes hazardous air pollutants as described under Section 112 of the Clean Air Act must develop a Leak Detection and Repair Plan (LDRP) to aid in reducing fugitive emissions [2]. The LDRP must be certified by the owner of the facility as meeting the fugitive emission criteria established by the EPA under the Clean Air Act. The plan is to be reviewed and updated, as required, once every three years, or within 90 days of a major modification at the facility. At the minimum, the LDRP:

(1) Develops a schedule and recordkeeping program for routine surveillance and/or monitoring of fugitive emissions.

(2) Establishes a written plan for detection and repair of leaks, and a reasonable schedule for repair.

(3) Provides a written plan for sampling procedures, housekeeping (e.g., small spill cleanup) and onsite waste handling.

(4) Develops recordkeeping procedures for all aspects of the LDRP and saves these records for one year.

(5) Establishes a written plan for specifying sufficient personnel to fulfill the LDRP, and provides a training program with a written manual.

5.2.2.5 Hazardous Chemical Spill Handling Plan--

Most plants' safety, disaster or operating plans and manuals do not fulfill the requirement for a spill-handling plan. The key to adequate spill-handling is decision-making. None of the above manuals or procedures supply the information required to make the decisions necessary to cope with the spill of a hazardous material. Thus, a chemical-spill-handling plan will fill an information need, but will not program decisions.

In a spill-handling plan, the decisions that must be made in a spill incident are defined. First, the plant or plant superintendent must accept the fact that a spill has occurred, based on information from his monitoring systems. The most immediate steps are those aimed at the protection of human life. If the information obtained about the location and nature of the leak/spill shows that the threat to life is "immediate and great," the decision should be to "shut down - all persons immediately take cover." Otherwise, the decision should be to "cleanup the area."

The "immediate cover" for persons is a spill response usually described by the plant disaster/emergency plan, whereas the protection of employees during the "cleanup the area" procedure is ordinarily contained in a safety plan. It is the lack of information between these two extremes that the spill-response plan fills.

Once a spill-response leader has been chosen, the decision-making process continues toward containment actions and disposition procedures. Figure 5-3 diagrams the decision-making process and information needed in a spill-handling situation, as well as the requirements for improving the spill response.

A spill-handling plan is written as an easy-to-consult document for decision-making, and includes:

(1) Monitoring all possible spills of materials

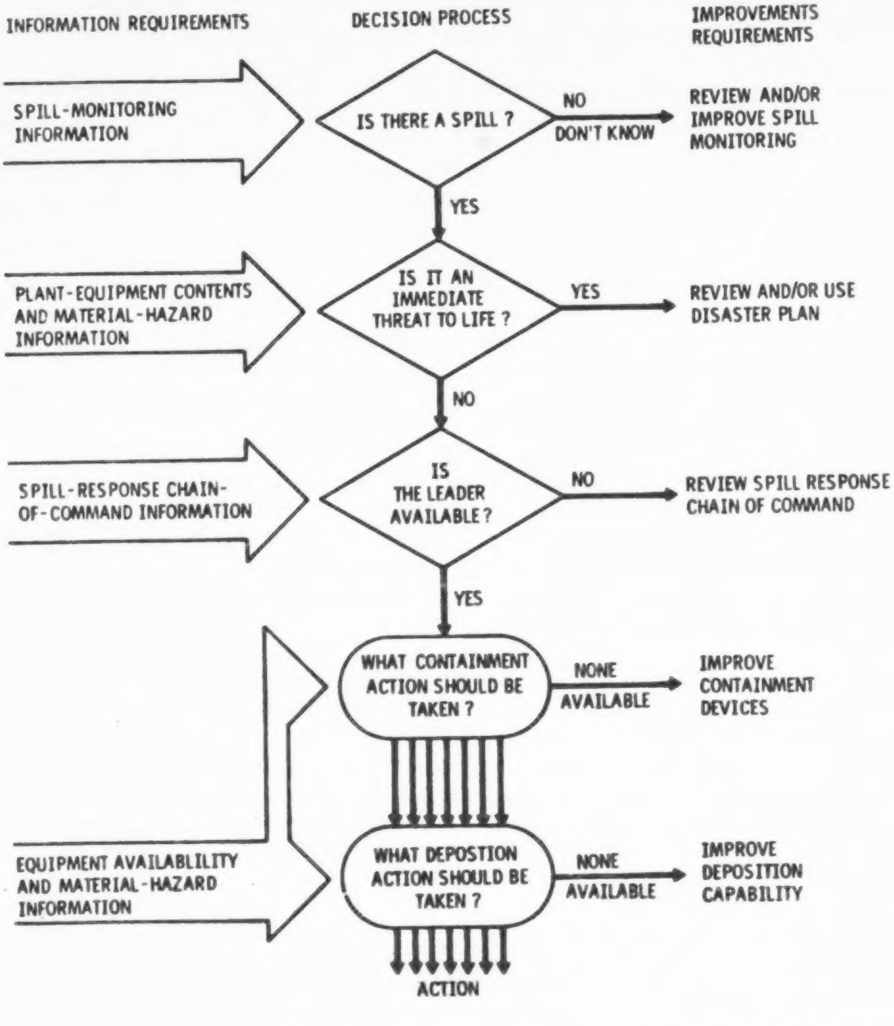

INFORMATION REQUIREMENTS
DECISION PROCESS
IMPROVEMENTS REQUIREMENTS
SPILL-MONITORING INFORMATION
IS THERE A SPILL ?
NO
DON'T KNOW
REVIEW AND/OR IMPROVE SPILL MONITORING
YES
PLANT-EQUIPMENT CONTENTS AND MATERIAL-HAZARD INFORMATION
IS IT AN IMMEDIATE THREAT TO LIFE ?
YES
REVIEW AND/OR USE DISASTER PLAN
NO
SPILL-RESPONSE CHAIN-OF-COMMAND INFORMATION
IS THE LEADER AVAILABLE?
NO
REVIEW SPILL RESPONSE CHAIN OF COMMAND
YES
WHAT CONTAINMENT ACTION SHOULD BE TAKEN ?
NONE AVAILABLE
IMPROVE CONTAINMENT DEVICES
EQUIPMENT AVAILABLILITY AND MATERIAL-HAZARD INFORMATION
WHAT DEPOSTION ACTION SHOULD BE TAKEN ?
NONE AVAILABLE
IMPROVE DEPOSITION CAPABILITY
ACTION

Figure 5-3. Spill-response diagram illustrating the interrelating information available, decisions to be taken, and improvements needed [3].

(2) Identifying of all plant equipment and other contents it may have (can be separated into convenient process groupings or modules)

(3) Describing hazards of materials that would comprise potential spills

(4) Designating the chain of command during a spill incident

(5) Specifying equipment available for containment, and disposition alternatives in response to a spill.

Every spill-handling plan has seven relatively independent parts that fulfill the five needs mentioned above. These parts are kept as autonomous as possible to facilitate the upgrading of each one. The seven parts are:

(1) List of contacts for spill emergencies, including plant/shift individuals, safety personnel, environmental control personnel, and government agency contacts, with home and office telephone numbers.

(2) Process flowsheets, showing primarily those pieces of equipment containing sufficient volume of material to constitute a potential spill problem.

(3) Site map.

(4) Chemical-effects list for all hazardous materials located within the boundaries of the plant.

(5) Monitoring checklist, consisting of a matrix indicating how equipment is monitored for potential spills.

(6) Containment alternatives matrix, describing the series of containments that occur in sequential order for various process equipment.

(7) Chemical-disposition alternatives, including a listing of equipment that are considered alternative places of material disposition for recovery, treatment, ultimate disposal.

5.2.2.6 Facility Security

Incineration facility security is management's responsibility. Basic security problems are protection of property and controlling access to the facility. Security procedures for hazardous waste disposal facilities are described in the Federal Register, Vol. 45, No. 98, Part 265 - Interim Status Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities, Subpart B - General Facility Standards, 265.14 Security, pg. 33235, May 19, 1980.

5.2.2.7 Operator Practices and Training

Operator practices and training of personnel ensure the smooth, efficient running of a hazardous waste incineration facility. Some of the areas covered under practice and training include:

(1) Selection of personnel, pre-employment physicals, periodic examinations
(2) Training; e.g., supervisory, operator, emergency
(3) Operating manual use; e.g., development of the manual, process description, material specifications, safety considerations
(4) Instruction of personnel
(5) Start-up and shut-down procedures; e.g., problems of start-up, normal shut-down, emergency shut-down
(6) Maintenance and inspection
(7) Preparation for emergencies; e.g., recognition, alarms, simulated emergencies, disaster drills

Operator training procedures and rules are described in the Federal Register (as cited in Section 5.2.2.6), 265.16 - Personnel Training.

5.2.2.8 Loss Prevention Program

A loss prevention program embodies many of the facets of an emergency handbook, operations manual, and personnel training. Usually, loss prevention encompasses a whole facility concept and can include other concerns such as:

(1) Accident prevention
(2) Industrial Health and Hygiene
(3) Environmental Control
(4) Fires and explosions
(5) Fire prevention measures
(6) Explosion prevention measures

5.3 WASTE RECEIVING AREA

The type and nature of hazardous waste received at an incinerator facility will dictate the design and equipment of the waste receiving area. The physical types of hazardous waste which may be received are:

(1) Liquid
(2) Containerized materials, liquid and solids
(3) Dry solid materials
(4) Wet solid materials
    (a) Pumpable
    (b) Nonpumpable.

The types of receiving equipment for unloading can be divided into three general areas:

(1) Pumpable liquid transfer
(2) Container transfer
(3) Bulk solids transfer.

Figure 5-4 shows a generalized flow diagram of handling procedures for incineration of hazardous wastes. Careful consideration must be given to the layout, safety, and recordkeeping arrangements of the waste receiving area. Unloading material offers one of the greatest spill or toxic exposure

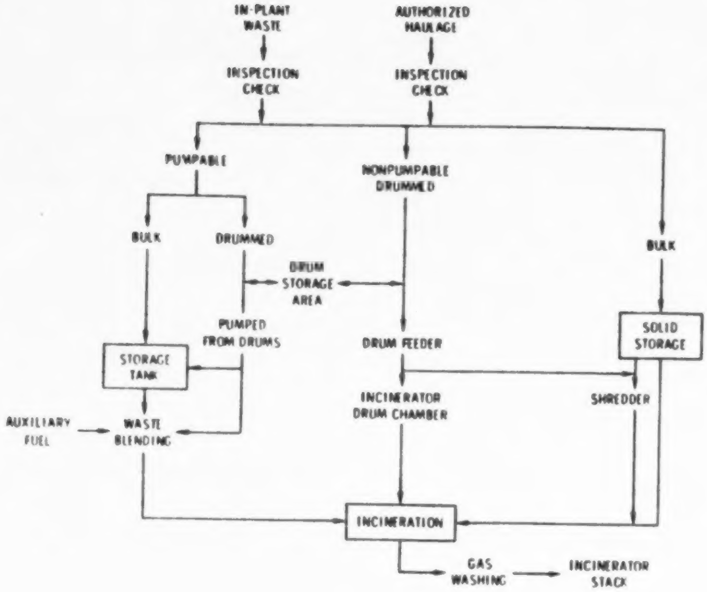

IN-PLANT WASTE
AUTHORIZED HAULAGE
INSPECTION CHECK
INSPECTION CHECK
PUMPABLE
NONPUMPABLE DRUMMED
BULK
DRUMMED
BULK
DRUM STORAGE AREA
PUMPED FROM DRUMS
DRUM FEEDER
SOLID STORAGE
STORAGE TANK
INCINERATOR DRUM CHAMBER
SHREDDER
AUXILIARY FUEL
WASTE BLENDING
INCINERATION
GAS WASHING
INCINERATOR STACK

Figure 5-4. Flow diagram showing handling procedures for incineration of hazardous wastes.

potentials at a hazardous waste facility. For recordkeeping, the waste receiving area poses the first interface with the transporter and manifest system.

5.3.1 Typical Operations and Layouts

A detailed flow sheet is a useful guide in laying out receiving areas, particularly those handling hazardous materials. The nature of the materials and handling procedures can be studied and provisions made to eliminate or control hazards.

Access to the incinerator facility will most likely be by truck or rail. (An inspection procedure will be required for all incoming waste.) Figure 5-5 illustrates a receiving area layout of a facility designed to accommodate both forms of transport. Most receiving areas for liquids will consist of a docking area, pumphouse, and storage facilities. For solid materials the pumphouse is replaced with mechanical or pneumatic conveyor devices. For receipt of containers, a suitable docking area with conveyors and inspection appropriate to the hazardous nature of the containers is necessary. Later sections describe in greater detail some of the equipment, handling procedures, and safety requirements for each form of hazardous waste received.

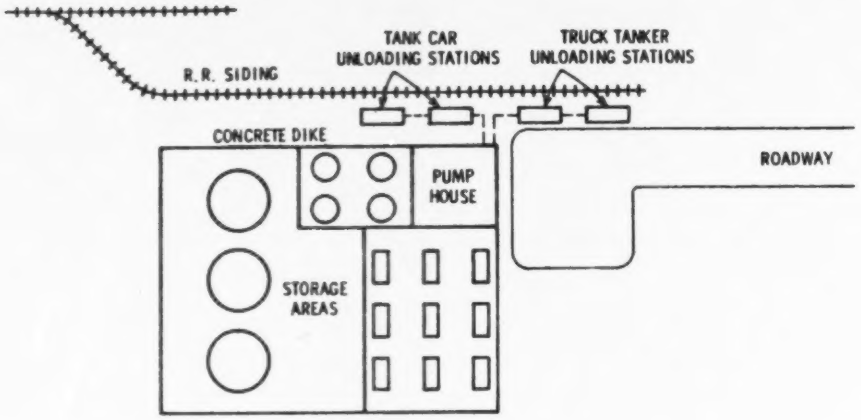


Figure 5-5. Layout for liquid receiving area.

5.3.2 Laboratory for Waste Verification and/or Characterization

Analytical data should be made available for all wastes to be incinerated. The physical and chemical properties and the combustion characteristics of each chemical waste or general classification of wastes, will be determined before incineration. Only after such analysis can successful waste disposal be carried out safely and without violation of air or water pollution regulations as set forth by state and federal agencies.

A minimal but complete laboratory facility requires a working area, including office facilities, of about 2,400 sq ft. Provisions are made for air, water, gas, and electricity, preferably both AC and DC. The laboratory furniture includes benches, sinks, fume hood, shelving, glassware racks and a refrigerator. Good lighting and air-conditioning are also important. Identification of laboratory equipment needed for analyses of chemical wastes follows. Specific requirements depend on the types of wastes to be processed and type of incinerator used. If the equipment for sophisticated analytical methods is not available in-house, the analyses can be performed by commercial analytical laboratories.

(1) Typical laboratory equipment to determine physical properties:

(a) Specific gravity balance - specific gravity of liquids.

(b) Brookfield viscosimeter - viscosity measurement of liquids and sludges.

(c) Imhoff cones and centrifuge with graduated tubes -measurement of percent solids by volume.

(d) Sieving machine for screen analysis (to 100 micron) and HIAC particle counter (100-5 micron) - particle size measurement.

- (e) Cleveland open cup flash point tester - flash and fire point determinations.
- (f) Oven and balances - percent solids and moisture by weight.
- (g) Gas chromatograph-mass spectrometry and infrared apparatus to identify organic substances which may be toxic.
- (h) Differential thermal analyzer - explosion characteristics and fusion temperature.
- (i) Juno meter or equivalent - sensitive to alpha, beta and gamma rays for radioactivity.

(2) Laboratory equipment to determine chemical properties.

- (a) Muffle furnace, oven, balances - for percent ash by weight.
- (b) Orsat, fyrite techniques for flue gas analyses to provide data for excess air calculations.
- (c) pH meter and automatic titrator - acidity and alkalinity measurement.
- (d) Emission spectrograph for concentration and presence of metals.
- (e) Atomic absorption spectrometer for concentration of metals and elements.
- (f) Optical microscope for particulate characterization down to the sub-micron size. Electron microscope may be required for some sub-micron determinations.

(3) Laboratory equipment to determine combustion properties:

- (a) Calorimeter for heating value and combustibility.
- (b) Orsat (previously listed) for CO_2, CO, O_2, H_2 and N_2 analysis.
- (c) Flue gas analyzer (previously listed) for analysis at various excess air rates.
- (d) Mass spectrometer (previously listed) for hazardous products of combustion.

Reliable, bench-scale, chemical incineration equipment is generally unavailable. The present practice appears to follow the line of waste characterization, physical, chemical and combustibility analysis followed by a test burn in pilot or plant scale equipment.

5.3.3 Liquids Unloading

Liquids will arrive in bulk in tank cars or tank trucks by either truck or rail. Standard rail tank cars vary in capacity from 6,000 to 26,000 gallons and tank trucks carry up to 10,000 gallons. Figures 5-6 and 5-7 illustrate typical tank cars with parts and nomenclature identified.

The unloading stations are not normally located near important buildings or facilities. The site is arranged so that escaping liquid will flow to a safe location by utilizing the natural grade or by providing diversionary dikes or drains. (For more information, see Section 5.3.3.1). When possible, 50 feet or more of clear space is provided between unloading stations and buildings.

Hazardous liquids and "pumpable" materials are transferred through piping by pump, gravity flow, or compressed-gas displacement. Pumping systems are most commonly used and have an inherent safety advantage in that they can easily be arranged so that the flow of liquid ceases when the pump is stopped. Either direct-displacement or centrifugal pumps can be purchased in a wide variety of capacities suitable for a wide range of liquids.

The safest method of unloading tank cars or trucks is through the top by means of a pump, as shown in Figures 5-8 and 5-9, which also illustrate provisions for grounding and bonding to prevent static electricity discharges. Many tank cars are equipped with permanent unloading connections in the dome. For cars not so equipped, special covers are available to replace the dome cover during unloading. Bottom unloading, unloading by siphoning, or unloading by air pressure is undesirable, since accidental movement of the tank car during unloading may result in the escape of the entire contents of the car. Bottom unloading may be tolerated under favorable conditions if a remote control or a heat-actuated automatic shutoff is provided at the tank car connection.

Tank trucks are usually unloaded from the bottom by gravity or by pumps mounted on the vehicle. These methods are considered acceptable.

For the best methods when transferring liquid wastes:

(1) Positive-displacement pumps are preferred

(2) Centrifugal pumps are suitable for flammable-liquid service but cannot be used as shutoffs.

Positive-displacement pumps are preferred because, unlike centrifugal pumps, they afford a reasonably tight shutoff and prevent siphoning when not in operation. A relief valve is provided downstream of positive-displacement pumps, of sufficient capacity to prevent excess pressure in the system. The relief-valve discharge is then piped back to the supply source or to the suction side of the pump. With liquids having closed-cup flash points of 0°F or lower, the relief valve should be piped to the storage tank; otherwise the churning action of the pump might cause dangerous overheating.

Centrifugal pumps are suitable for flammable-liquid service but cannot be used as shutoffs, since they usually must take suction under a head. Submerged or

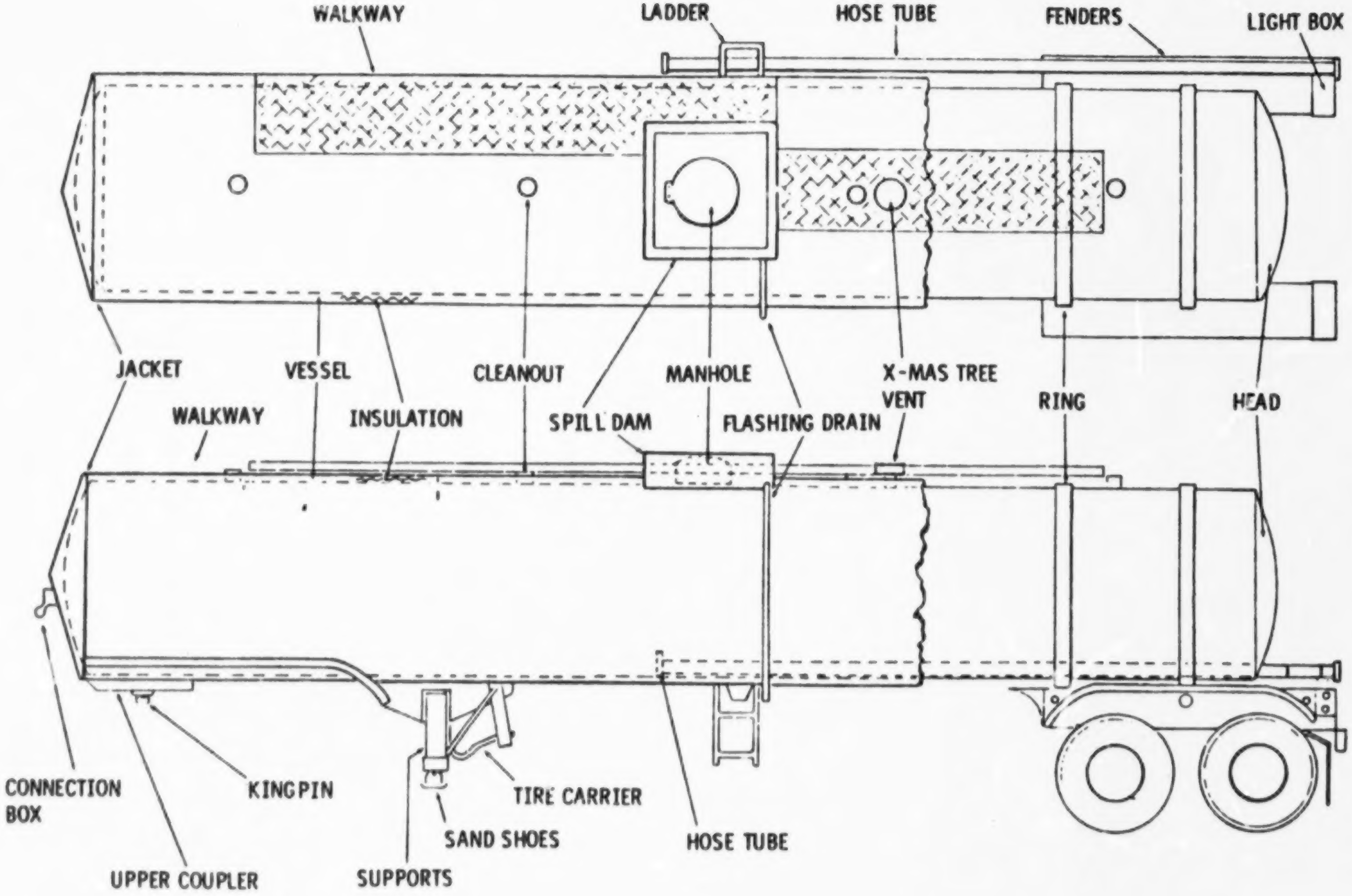
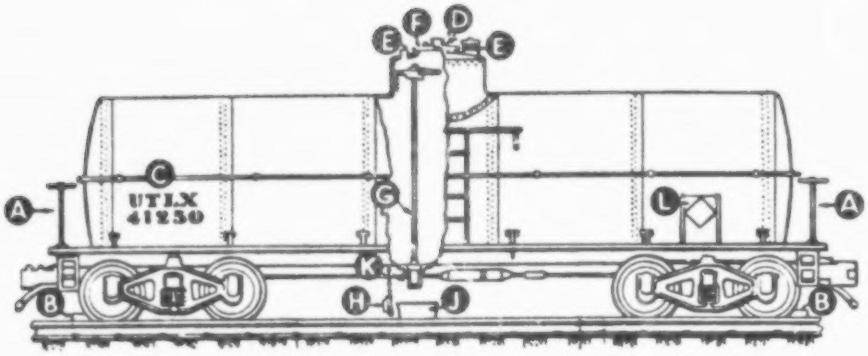
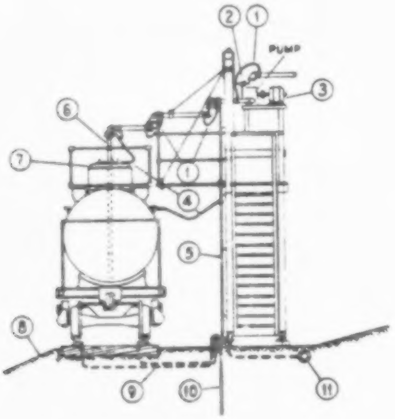

WALKWAY
LADDER
HOSE TUBE
FENDERS
LIGHT BOX
JACKET
VESSEL
CLEANOUT
MANHOLE
X-MAS TREE VENT
RING
HEAD
WALKWAY
INSULATION
SPILL DAM
FLASHING DRAIN
CONNECTION BOX
KINGPIN
TIRE CARRIER
SAND SHOES
HOSE TUBE
UPPER COUPLER
SUPPORTS

Figure 5-6. Typical tank trailer (car) with parts identified [4].



A. CAR BRAKE
B. WHEEL BLOCK
C. IDENTIFICATION NUMBER
D. CAR SEAL
E. SAFETY VALVE
F. DOME COVER
G. OUTLET LEG VALVE
H. OUTLET LEG CAP
J. DRAIN PAN
K. OUTLET NOZZEL
L. "FLAMMABLE" CARD

Figure 5-7. Typical tank car with parts identified [5].



1. BONDING WIRE ATTACHED WITH GROUND CLAMP
2. RELIEF-VALVE BYPASS
3. EXPLOSIONPROOF MOTOR
4. INSULATED FLEXIBLE GROUNDING CABLE ATTACHED TO TANK CAR WITH GROUND CLAMP; NOT SMALLER THAN NUMBER 4
5. NO. 4 STRANDED CABLE SECURED TO PLATFORM COLUMN
6. NONFERROUS TUBE
7. SAFETY-DOME COVER
8. GROUND SLOPING AWAY FROM IMPORTANT FACILITIES
9. BARE-COPPER CONDUCTOR
10. GROUND ROD DRIVEN TO PERMANENT MOISTURE LEVEL
11. WATER MAIN, IF AVAILABLE

Figure 5-8. Tank car unloading station [6].

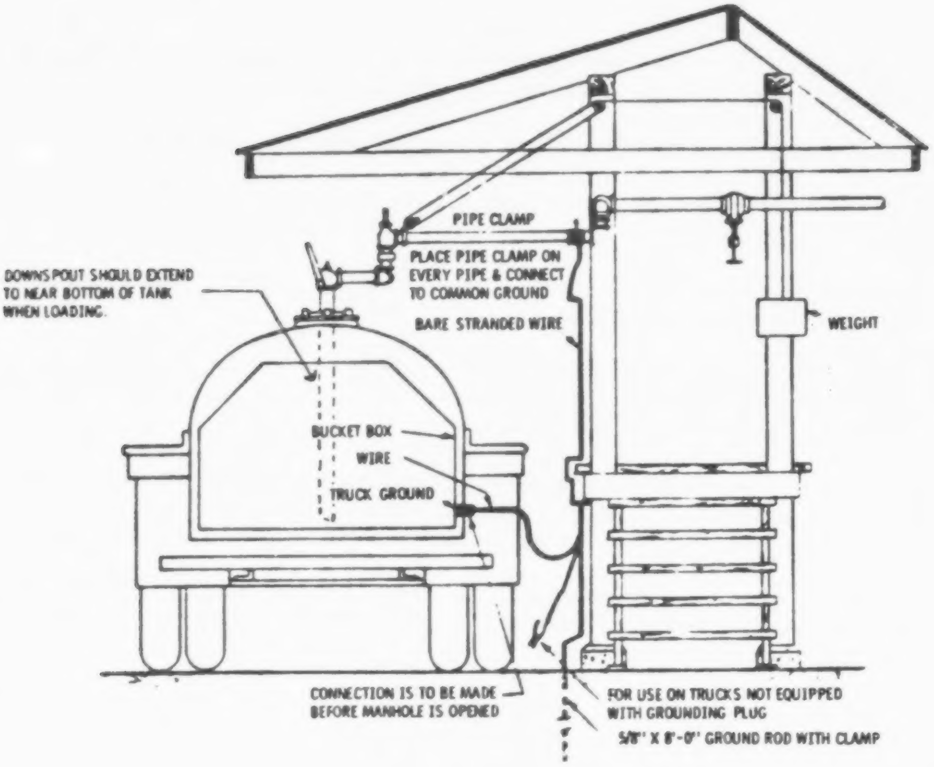

PIPE CLAMP
DOWNSPOUT SHOULD EXTEND TO NEAR BOTTOM OF TANK WHEN LOADING.
PLACE PIPE CLAMP ON EVERY PIPE & CONNECT TO COMMON GROUND
BARE STRANDED WIRE
WEIGHT
BUCKET BOX
WIRE
TRUCK GROUND
CONNECTION IS TO BE MADE BEFORE MANHOLE IS OPENED
FOR USE ON TRUCKS NOT EQUIPPED WITH GROUNDING PLUG
5/8" X 8'-0" GROUND ROD WITH CLAMP

Figure 5-9. Bonding and grounding of a flammable liquid tank truck and loading rack [5].

deep-well (vertical-shaft) centrifugal pumps mounted on tanks are satisfactory if the pump and bearings are cooled by the liquid being pumped. This is to prevent dry rotating parts from operating in the vapor space of the tank.

A gravity feed system has the disadvantage of being more difficult to arrange for prompt automatic or manual shutoff than unloading by pumping. Another disadvantage is that gravity usually maintains constant pressure on the system, whereas pumps can be easily arranged to permit pressurizing only during demand. If very volatile liquids cause vapor lock when pumped by conventional methods, gravity transfer may be necessary; it is required for many processing operations.

Some of the safety precautions for a gravity feed system are:

(1) Installation of emergency shutoff valves in all gravity transfer systems.

(2) Location of such valves as close to the source as possible.

Inert gas transfer methods, owing to the compressible nature of the transfer medium, have the same disadvantage as the gravity system. In the event of breakage or leakage, flow from the system will be continuous. Such systems also introduce the complication of pressure storage tanks.

Among the disadvantages of the inert gas transfer methods are these:

(1) A considerable amount of liquid may be discharged in the event of pipe failure or careless valve operation.

(2) Because vapor-air explosions are extremely violent at high pressure, transfer by compressed air should be avoided.

(3) Tanks for inert gas transfer systems have to be constructed, installed, and tested in accordance with ASME or other recognized codes for unfired pressure vessels.

(4) The gas pressure is regulated at the minimum needed to force the liquid through the transfer system, and a relief valve with a slightly higher setting downstream must normally be installed.

(5) Provisions need to be made for automatically shutting off the supply of inert gas and for bleeding the gas pressure from the flammable-liquid system in event of fire.

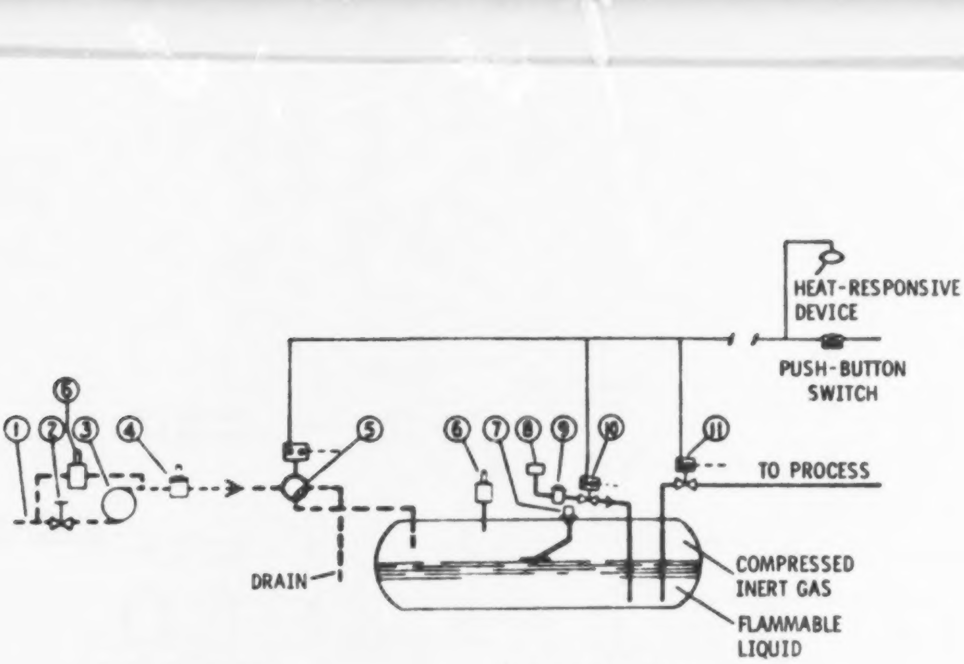
Transfer can be made by nitrogen, carbon dioxide, or other inert gases. The system is under constant pressure, and the compressibility of the transfer medium results in discharge of considerable liquid if there is pipe failure or careless valve operation.

A schematic diagram illustrating the inert gas transfer method is shown in Figure 5-10.

Fail-safe transfer lines primarily intended for use in transferring hazardous liquids between a mobile transporter and storage facility have been developed [7]. The operating principle is based on measurement of flow rate at the inlet and outlet of the transfer line, and detection of a leak through comparison of the two rates.

The system consists of four items: an inlet assembly, a flexible hose, an outlet assembly, and a control module. It is designed to transfer hazardous fluids, and to automatically close both the inlet and outlet valves upon detection of a leak. It will also cause the inlet and outlet valves to close if electrical power is lost, the valve operating air pressure is out of tolerance, or if any cable is severed. Figure 5-11 shows a simplified diagram of the system.

The inlet and outlet assemblies are shown in Figure 5-12. They are identical, except that a strainer is included on the inlet assembly only. The transfer hose is a 2-inch diameter, 50 ft. length of steel-reinforced steam hose, designed to carry about 100 gpm. The control module is housed in an explosion-proof junction box, consisting primarily of a simple hardwired computing device [7].


HEAT-RESPONSIVE DEVICE
PUSH-BUTTON SWITCH
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑥
TO PROCESS
DRAIN
COMPRESSED INERT GAS
FLAMMABLE LIQUID

1. INERT GAS SUPPLY LINE
2. MANUAL CONTROL VALVE
3. GAS COMPRESSOR
4. PRESSURE-REGULATOR VALVE
5. SOLINOID-OPERATED THREE-WAY TWO-PORT VALVE. WHEN CIRCUIT TO SOLINOID IS COMPLETED, VALVE INLET IS CONNECTED TO OUTLET TO SUPPLY INERT GAS TO TANK. SHOWN WITH CIRCUIT TO SOLENOID BROKEN; VALVE DISCHARGE IS CONNECTED TO DRAIN TO RELIEVE PRESSURE ON TANK.
6. RELIEF VALVE
7. LIQUID-LEVEL DIAL INDICATOR
8. FILL CONNECTION
9. STRAINER
10. SOLINOID VALVE. INTERLOCKED SO THAT IT WILL BE OPEN ONLY WHEN VALVE 5 ON INERT GAS SUPPLY LINE IS IN THE POSITION SHOWN AND VALVE 11 ON DELIVERY LINE IS CLOSED.
11. SOLINOID VALVE. ARRANGED FOR MANUAL CONTROL AND FOR AUTOMATIC SHUTOFF IN EVENT OF FIRE AT PROCESS.

Figure 5-10. Compressed inert gas transfer method [6].

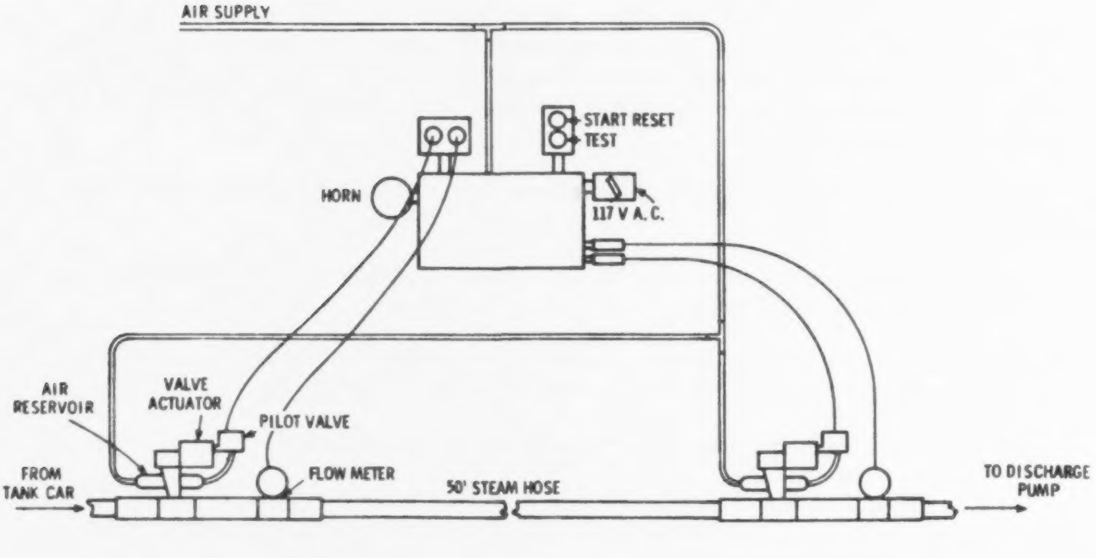

AIR SUPPLY
START RESET
TEST
HORN
117 V A. C.
AIR RESERVOIR
VALVE ACTUATOR
PILOT VALVE
FROM TANK CAR
FLOW METER
50' STEAM HOSE
TO DISCHARGE PUMP

Figure 5-11. Fail safe transfer line for hazardous fluids [7].

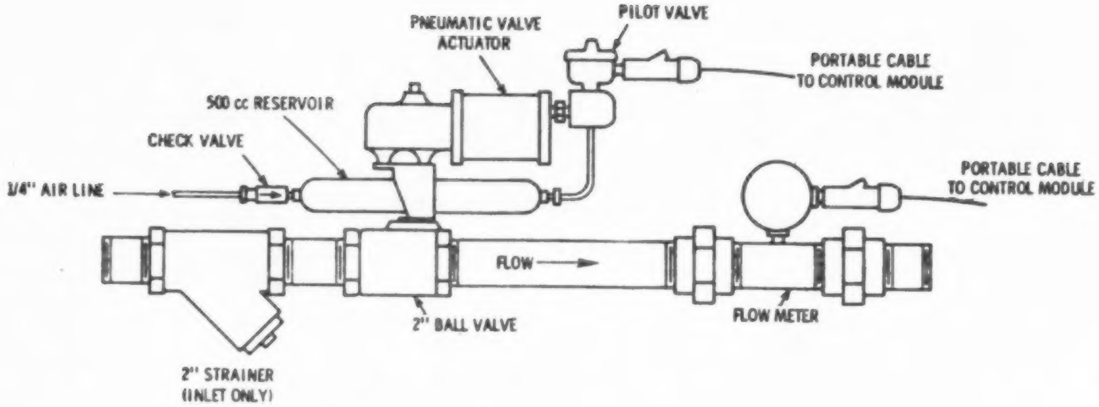

PNEUMATIC VALVE ACTUATOR
PILOT VALVE
PORTABLE CABLE TO CONTROL MODULE
500 cc RESERVOIR
CHECK VALVE
1/4" AIR LINE
PORTABLE CABLE TO CONTROL MODULE
FLOW
2" BALL VALVE
FLOW METER
2" STRAINER (INLET ONLY)

Figure 5-12. Fail safe transfer line inlet and outlet assemblies [7].

The device will reliably detect leaks of 0.5% or greater. Average fluid loss before valve actuation (closing at 85 gpm and 0.5% leak rate setting) was 250 mL. It should be noted that the extremely low fluid loss before shutdown is only a measure of the device reaction time and not of the total fluid loss that may be experienced in the event of a leak. Fifty feet of 2-inch hose holds about 8 gal of fluid; all of which could be lost through the leak after shutdown.

5.3.3.1 Safety/Emergency Provisions--

Hazardous fluid unloading and transfer operations offer one of the highest likelihoods of accidents; i.e., fire, spills, or worker exposure. Technical bulletins of the Chemical Manufacturers Association (CMA) and the American Petroleum Institute (API) provide excellent guidance for the unloading of tank cars and tank trucks [8-11].

Some of the design provisions and procedures for safely unloading hazardous liquids include:

(1) The condition of the cars is examined, and any leaks are to be reported immediately.

(2) Before unloading starts the area is checked to be sure it has no exposed lights, fires, or other sources of ignition.

(3) Vents on tank cars are protected by flame arresters.

(4) In all cases, personnel should be thoroughly trained and have been given written instructions suitable for each material they will handle.

(5) Adequate personal, protective equipment have been furnished for those involved in the loading and unloading of tank cars. For materials that are corrosive to the skin or that may be absorbed through it, full protective clothing with face masks, rubber gloves, rubber shoes, etc., is required. When materials that have toxic vapor or gas are unloaded, personnel should be equipped with airline respirators or self-contained breathing equipment. Protective equipment not available at the site should be obtained even though this may mean some delay in making the transfer.

(6) First aid and medical procedures are worked out in advance and posted in the unloading area. Where unusually toxic substances are handled, medical personnel will have information on the characteristics of the material and on the medical management needed for any material they may encounter.

(7) Fire extinguishers of adequate type for the material handled are distributed throughout the area.

(8) Personnel responsible for unloading stay in the immediate vicinity of the operation at all times, and ascertain that all conditions are normal.

(9) An emergency shower and an eyewash device is available at each loading location. Preferably, these devices are tied to an alarm system that would bring help to any man making use of them.

(10) Safe access to the top of the vehicle is one general safety requirement for liquid unloading. This is particularly important for top unloading, but it may also be necessary for operations such as gauging or sampling. Thus, loading racks with suitable ladders, platforms, gangways, or even railings permanently affixed to the vehicle are usually required.

(11) Keeping liquid-unloading facilities usable in adverse weather conditions, such as icing, may be difficult, but every effort must be made to keep them safe. Good general illumination, especially at night, is far preferable to providing the operator with an extension light, which he might drop.

(12) Steel pipe and swing joints or flexible hose of the standard metal type are usually used for connections to tank cars or tank trucks. Metal-reinforced rubber hose of a type resistant to the material being handled is acceptable but less desirable. See Section 5.13 on materials compatibility.

(13) Each line and connection should be clearly identified to avoid intermixing materials.

(14) Liquids that require heat within the tank car for pumping purposes should be received only in cars equipped with heater coils. The minimum steam pressure necessary to being the liquid to a fluid

state is used. A regulator adjusted to this pressure is installed in the steam line, and a relief valve with a slightly higher setting is provided downstream.

(15) Some tank cars and tank trucks have interior linings of rubber or plastic of various kinds. When such cars are being unloaded, special care must be taken to prevent damage to the lining.

(16) Pumps are preferably located outdoors so that fire at the pump will not expose property of appreciable value. They should not be located inside diked areas. Pumps are sometimes located in small detached noncombustible pump houses or in cutoff rooms of main buildings. When they are located indoors and handle flammable liquids with flash points below 110°F, positive low-level exhaust ventilation of 1.0 $ft^3/min\text{-}ft^2$ of pumproom floor area is recommended. Natural ventilation is acceptable for less hazardous liquids.

(17) Where flammable liquids are handled in a pump house, motors can be partitioned and sealed off from the rest of the pump house, or can be of a type approved for use in flammable atmospheres. It is a good operating and safety practice to have a well-marked master cutoff switch outside the building. However, consideration is normally given to locating flammable liquid pumps outside of buildings whenever feasible.

(18) As a fail-safe precaution, an interlocked warning light or physical barrier system is often provided in unloading areas to prevent vehicular departure before complete disconnect of flexible or fixed transfer lines.

5.3.3.2 Spill and Runoff Containment--

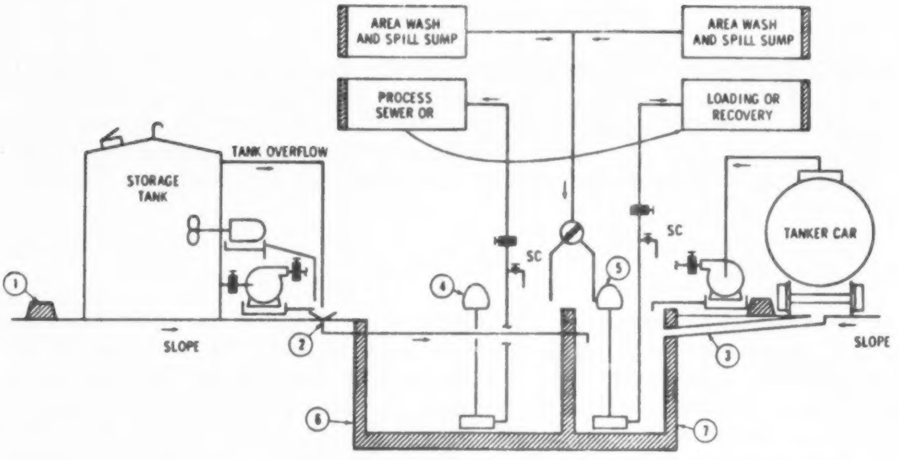
Drainage from the unloading area is collected or diverted to allow runoff of any spills or runoff from rainfall to permit recovery or at least proper disposal. The basic objective of secondary containment is to prevent the discharge of hazardous materials to waterways, sewer systems, or groundwaters. Containment systems which fail under rainstorm conditions are considered inadequate. To the extent feasible, such containment is designed to hold 110% of the largest unit handled (or largest unit contents plus the maximum 24-hr/10-yr rainfall event, if greater).

For tank trucks a system of containment curbs are used for unloading areas, using ramps to provide truck access into the confines of the containment curb.

A lined trenching system encompasses the railroad tank car unloading area. The trench is designed to carry away any spill or runoff to a catchment basin or holding pond for later treatment. Figure 5-13 illustrates a containment curb type spill catchment system, depressed area form.

5.3.3.3 Static Electricity Prevention--

Static electricity is generated when fluid flows through a pipe or from an orifice into a tank. The principal hazards created by static electricity are those of fire and explosion, which are caused by spark discharges containing


AREA WASH AND SPILL SUMP
AREA WASH AND SPILL SUMP
PROCESS SEWER OR
LOADING OR RECOVERY
STORAGE TANK
TANK OVERFLOW
TANKER CAR
SC
SC
SLOPE
SLOPE
①
②
③
④
⑤
⑥
⑦

ITEM	DESCRIPTION OF PROTECTION	OPERATION/EQUIP. PROTECTED	HAZARD
1	DIKE	TANKS	SPILLS, WASHING
2	RAISED DRAIN	OVERFLOW, DRIPS	CONC. SPILLS
3	TRENCH DRAIN	TANKCAR	UNLOAD, SPILLS
4, 5	SUMP PUMP	PROCESS SEWER	SLUG DISCHARGE
6	DILUTE SUMP	TANK MAT	SPILLS
7	CONC. SUMP	PROCESS SEWER	DISCHARGE

Figure 5-13. Containment curb type spill catchment system, depressed area form [12].

sufficient energy to ignite any flammable or explosive vapors or dust present. A point of great danger from a static spark is the place where a flammable vapor may be present in the air, such as a delivery hose nozzle.

The terms "bonding" and "grounding" often have been used interchangeably because the terms are poorly understood. Bonding is done to eliminate a difference in potential between objects. Grounding is done to eliminate a difference in potential between an object and ground. Figures 5-8 and 5-9 (Section 5.3.3) illustrate bonding and grounding of tank cars during unloading operations. Figure 5-14 shows rail joint bonding and track grounding.

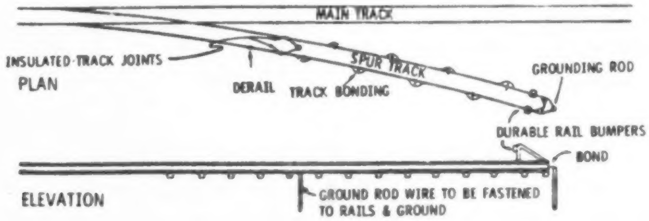

MAIN TRACK
INSULATED TRACK JOINTS
PLAN
DERAIL
TRACK BONDING
SPUR TRACK
GROUNDING ROD
DURABLE RAIL BUMPERS
BOND
ELEVATION
GROUND ROD WIRE TO BE FASTENED TO RAILS & GROUND

Figure 5-14. A tank car unloading siding showing rail joint bonding, insulated track joint, detail, and track grounding [5].

When unloading tank cars through open domes, it is best to use a downspout long enough to reach the tank bottom. Generally, tank cars need not be separately grounded because the resistance of the natural ground through the tank car wheels and rails, and the resistance of piping, flexible metallic joints, or metallic swivel joints, are considered sufficiently low to protect against static electricity. For detailed information and exceptions to this generality, consult NFPA Standard No. 77, "Recommended Practice on Static Electricity."

5.3.4 Container Unloading

For hazardous wastes, the choice of container will usually be made from among various types of drums, barrels, and special bulk units. As is true in any bulk handling problem, the first step is to obtain information on the type of container which will be received with respect to its handling properties. Since it contains a hazardous waste, the container must then meet the regulations for its transportation set forth by the Department of Transportation and RCRA.

Containerized hazardous waste is most likely to arrive for unloading via rail boxcar or truck semitrailer. Due to economics of transportation, the carrying capacity of a trailer or boxcar will most likely be near the maximum. A 55-gal drum is the most popular form of container; a boxcar can carry 360 55-gal drums per carload.

In addition to liquid waste, certain dry materials require the strength, water tightness, weatherability, and general ruggedness of a steel drum. Standard specifications for steel drums have been established by the Department of Transportation; a typical specification is shown in Table 5-2. The heavier gage drums find use in transporting liquids.

The process for unloading trailers or cars differs by the waste and hauler. Drummed material may be placed on pallets or may rest on the bed of the trailer. In the latter case, the hauler may be involved with unloading and may manually handle the cargo. A common delivery condition for cargo touching the truck bed is "tail gate delivery", whereby the truck driver moves the packaged cargo to the tailgate of the trailer, and the recipient removes it.

Alternative methods include industrial trucks with drum-loading attachments, or fork-lifts for containers on pallets. Type EE battery-powered industrial trucks have the additional safeguards (electrical equipment enclosed to prevent emission of sparks) needed to work in hazardous locations; Type EX trucks, which are of explosion-proof or of dust tight construction, are also recommended.

After removal steel drums can be handled by gravity conveyors. However, steel drums should not be transported on wheel conveyors, because the chime, or lip, at the drum bottom gets hung up on the wheels. If roller conveyors are used, the rolls need to extend at least 2 in. beyond the outside surface of the chime, unless the drums are centered by guard rails. Drum loads up to 250 lb can be handled on a conventional 1.9-in. roller conveyor having rollers spaced at 3 in. and positioned at a 1-1/2 in. pitch.

TABLE 5-2. TYPICAL STEEL DRUM SPECIFICATION FOR HAZARDOUS MATERIALS [13][a]

Capacity, gal	Inside diameter	Inside height	Outside diameter	Overall height	Steel gage, body	Steel gage, cover	Steel gage, bottom	Steel gage, ring	Tare weight (approx.)[b]	DOT spec.
55[c]	22 1/2	32 11/16	23 27/32	34 13/16	16	16	16	12	64.5	17C
55[c]	22 1/3	32 11/16	23 27/32	34 13/16	18	16	18	12	55.5	17H
30[d]	18 1/4	27 5/16	19 19/32	29	18	18	18	12	37.5	17C & 17H

[a] All dimensions given in inches. Dimensions are within normal manufacturing tolerances of ± 1/16 in. (± 1/8 in. on height).

[b] Container weights shown are approximate and may vary within the allowable limits for manufacturers standard gage.

[c] On the 55-gal drum, a third rolling hoop, directly below the top rim, gives strength and rigidity to meet specifications.

[d] These drums meet Department of Transportation Specifications DOE 17H and DOT 17C for storage and shipment of hazardous materials. They also meet Rule 40 of the Uniform Freight Classification, and Rule 26C of the National Motor Freight Classification; DOT 17H drums also comply with ANSI standards.

Because of the difference in weights between empty and full drums, a roller pitch as high as 5 in. can be specified for empties, while a pitch of 3 in. may be sufficient for full drums. Both live-roller conveyors and belt-on-roller conveyors can also be used to convey drums.

A host of other special containers have been made for storing, shipping, and handling hazardous materials. Some of these units are designed to hold 2,000 lb or more; some designs include metal-walled containers equipped with specialized filling and discharge openings and rubberized containers. A major factor to be looked at when a facility receives these types of units is the total system concept of handling, with appropriate machinery and design taken into account.

Once a container has been unloaded, three possible options exist for distributing the contents:

(1) Place the container in storage.
(2) Pump the contents (liquid) into another storage tank.
(3) Dump the contents (bulk solids) into another receiver.

5.3.5 Bulk Solids Unloading

Hazardous waste bulk solids for incineration will arrive for unloading in hopper cars - both truck and rail. Due to the hazardous nature of the material transported, the hopper cars must be the covered type, typically with bottom unloading ports. Three types of unloading systems are used:

(1) gravity,
(2) pressure differential, and
(3) fluidized.

Figure 5-15 shows examples of fluidized unloading ports. Fluidized unloading is preferable for hazardous wastes when possible, because gravity unloading necessitates having a pit located under the rail spur.

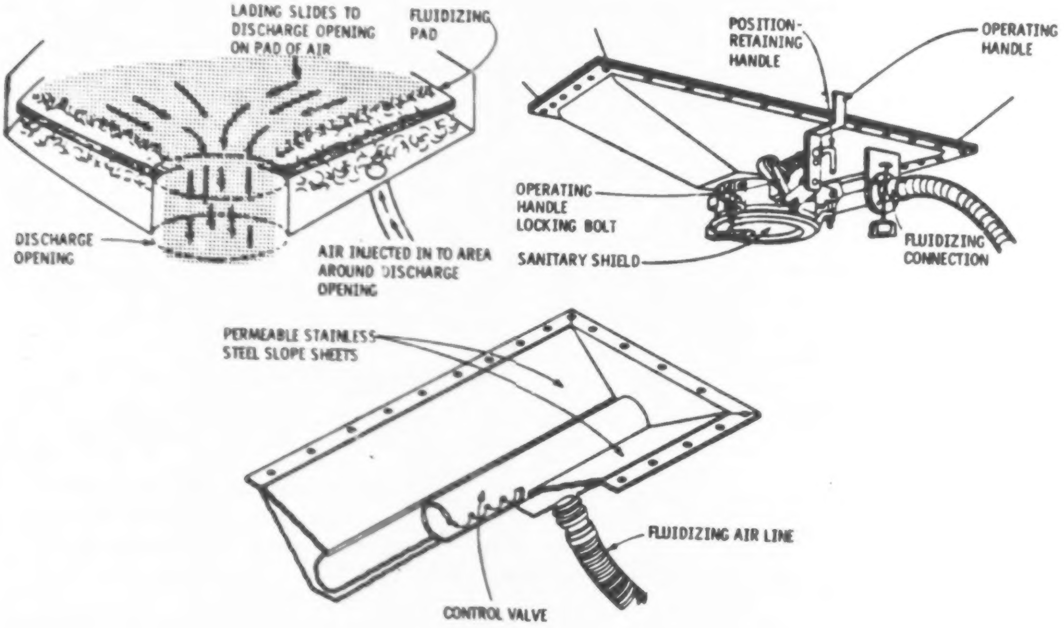

LADING SLIDES TO DISCHARGE OPENING ON PAD OF AIR
FLUIDIZING PAD
DISCHARGE OPENING
AIR INJECTED IN TO AREA AROUND DISCHARGE OPENING
POSITION-RETAINING HANDLE
OPERATING HANDLE
OPERATING HANDLE LOCKING BOLT
SANITARY SHIELD
FLUIDIZING CONNECTION
PERMEABLE STAINLESS STEEL SLOPE SHEETS
FLUIDIZING AIR LINE
CONTROL VALVE

Figure 5-15. Fluidizing outlets for hopper cars [14].

5.3.5.1 Mechanical Conveyors--

When a discharge pit is used for unloading, the material is then conveyed to storage via one or more of three methods:

(1) screw conveyor,
(2) belt conveyor, and
(3) bucket elevator.

The screw conveyor is one of the oldest and most versatile conveyor types. It consists of a long pitch, steel helix flight mounted on a shaft, supported by bearings within a U-shaped trough. Screw conveyors are generally easy to maintain and inexpensive to replace.

Belt conveyors consist of an endless belt moving horizontally or on an incline. Almost all belt conveyors for bulk solids use rubber-covered belts whose inner carcass provides the strength to pull and support the load. Belt conveyor slopes are limited to a maximum of about 30° with those in the 18-20° range more common. In an evaluation of a materials-handling system involving belt conveyors, the number of belt transfer points should be reduced to a minimum to cut degradation, dust, and cost. Elevation of all belt lines a few feet above ground will ease inspection, maintenance, and cleanup. Belt conveyors emit dust almost exclusively at the transfer points. Placing enclosures around transfer points can give effective dust control. A few simple rules are normally followed for dust control:

(1) Reduce the number of belt transfers point to a minimum

(2) Be generous in sizing enclosures

(3) Arrange enclosures in easily removable sections

(4) Provide access doors on enclosures

(5) Install skirting and curtains at openings.

Bucket elevators are the simplest and most dependable units for making vertical lifts. They can be totally enclosed to reduce fugitive dust emissions.

5.3.5.2 Pneumatic Conveyors--

Pneumatic conveyors are commonly used to transfer dry granular or powdered materials, both vertically and horizontally, to plant areas hard to reach economically with mechanical conveyors. The properties of a material determine whether or not it can be successfully conveyed pneumatically. The material must pass through piping and auxiliary equipment without clogging, degradation, or segregation, and be readily disengaged from the conveying air. Materials from fine powders through 1/4-in. pellets can be handled.

Pneumatic systems can be completely enclosed to prevent contamination, material loss, and dust emissions. Furthermore, some materials are better protected from adverse reactions when they are conveyed using an inert gas or dried air.

Pneumatic conveying systems can provide smooth, controlled, hands-off unloading of bulk rail cars. The unloading procedure begins with the insertion of a material pickup probe into the rail car's discharge port. The probe controls the material-to-air ratio, and probe kits are designed to fit all rail cars.

They consist of housing with slotted probes of varying lengths, designed to reach different areas or compartments across the rail car. An air intake filter is clamped to the car's discharge port opposite the material pickup connection, and a car hatch filter attaches to the top of the rail car to relieve vacuum created in the car by the material flow. Figure 5-16 illustrates pneumatic unloading of a railcar.

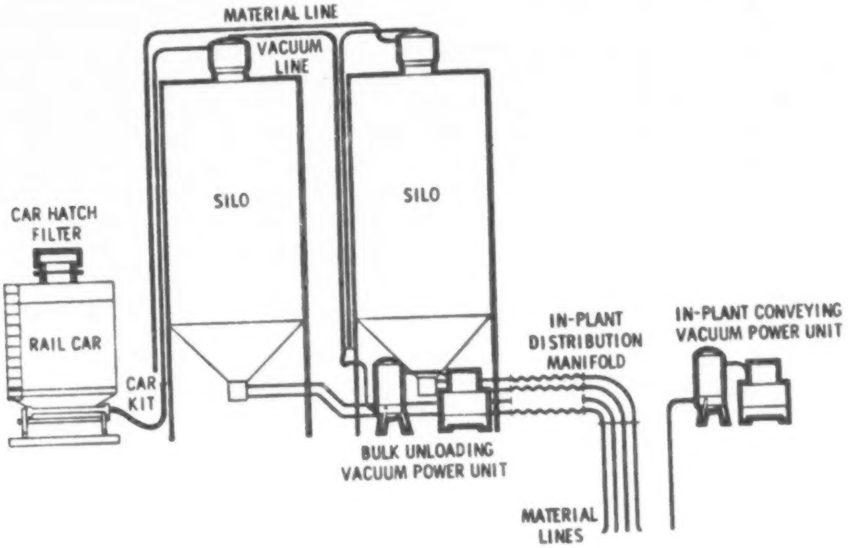

MATERIAL LINE
VACUUM LINE
SILO
SILO
CAR HATCH FILTER
RAIL CAR
CAR KIT
IN-PLANT DISTRIBUTION MANIFOLD
IN-PLANT CONVEYING VACUUM POWER UNIT
BULK UNLOADING VACUUM POWER UNIT
MATERIAL LINES

Figure 5-16. Diagram of pneumatic railcar unloading.

5.4 WASTE STORAGE AREA

The manner in which a waste is handled on-site is dependent on the nature of the waste (corrosivity, explosivity, etc.), plant storage facilities, and heat content of the fuel. Wastes received for incineration at a disposal facility are either incinerated directly (in some cases via pumping directly from the tank truck), or stored until they can be handled more conveniently. A plant operator may want to store some of the incoming wastes with higher heating values to possibly blend with other wastes which have heating values too low to support combustion alone. At some plants, waste blending occurs prior to storage. For a discussion on waste blending, see Section 5.5.

For further information on storage of hazardous waste in tanks, piles or containers, see The Permit Writer's Manual on each of those topics (prepared by Fred C. Hart Assoc., Inc.).

Storage capacity is based on:

- Seasonal inventory buildup
- Redundancy or excess incinerator capacity
- Maintenance schedules and downtime

- Operating schedules (i.e., number of shifts vs. inshipment rates)
- Amounts and nature of waste blending to be done.

Depending on the type of incinerator installation, storage facilities may be required to hold both liquid and solid hazardous wastes. If an incinerator cannot burn solids, facilities for solid storage are obviously not necessary.

A hazardous waste storage area is designed to address three problem areas:

(1) Segregation of incompatible corrosive and reactive waste types;

(2) Fire hazards due to flammable liquids and solids; and

(3) Toxic hazards to prevent human exposure during storage, transfer, and spill possibilities.

The safety and emergency design provisions for storing hazardous liquid wastes are described in Section 5.4.3.

5.4.1 Types of Storage

5.4.1.1 Liquid storage--

Liquid/fluid waste storage includes temporary holding tanks, batching tanks, main storage tanks, and transfer pumps (pumps and valving are discussed in Section 5.5). Holding tanks provide initial storage of wastes prior to final deposition of the material. Other tanks can store specific waste categories which have been analyzed, require segregation, and are ready for incineration. Batching tanks are used to prepare an 8-hr shift waste feed for the incinerator. Also, tanks may be needed to store fuel oil (or bottled gas) for incinerator ignition and auxiliary burners.

The storage tank farm facility is designed for liquids which may have high vapor pressure, will be corrosive, will contain suspended solids, and may be prone to polymerize. Tanks should be provided with nitrogen blanketing. Before storing, the suspended solids are largely removed to minimize equipment erosion/corrosion and valve sticking. Tank access is designed to facilitate ease-of-entry for cleaning in the event that solidification does occur, and it most certainly will at some time [15].

Container nomenclature is vague but, ordinarily, "tank" means a container designed to withstand pressures from atmospheric up to about 15 psig, whereas "vessel" refers to a container which can withstand external or internal pressures exceeding 15 psig. Tank pressure design of 15 psig is recommended [15]. Vapor pressures of 10 psig are not uncommon.

There are several basic types of storage tanks, as shown in Figure 5-17. The aids to design of tanks takes the form of specifications, rules, standards, and codes.

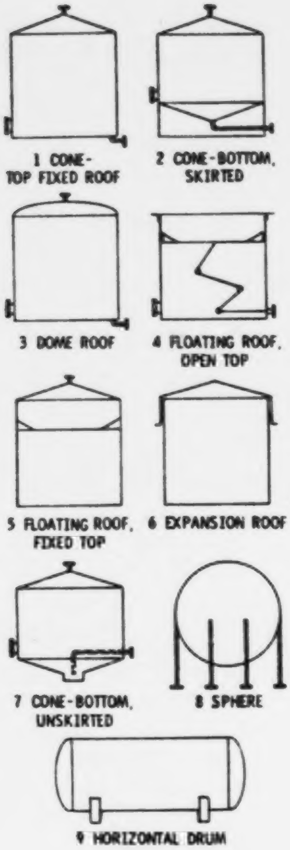

1 CONE-TOP FIXED ROOF
2 CONE-BOTTOM, SKIRTED
3 DOME ROOF
4 FLOATING ROOF, OPEN TOP
5 FLOATING ROOF, FIXED TOP
6 EXPANSION ROOF
7 CONE-BOTTOM, UNSKIRTED
8 SPHERE
9 HORIZONTAL DRUM

Figure 5-17. Typical shapes for storage vessels [16].

Any of the vessels noted above can be lined or coated with corrosion-resistant materials. All weld spatter is removed, and welds ground smooth or flush, depending on the type of coating to be applied. Tank nozzles must be large enough so a coating can be applied. Corrosion is an unavoidable problem. Grit scouring destroys surface passivation and promotes corrosion, another reason for screening the incoming waste [15].

Both vertical and horizontal tanks are available for storing liquids. Vertical tanks are more economical to install, and occupy less space, while horizontal tanks are easier to maintain and repair. Usually the lower maintenance generally required by horizontal tanks does not offset their higher cost and greater space requirements; hence, vertical tanks are normally recommended. If, however, it appears that future compartmentation of the tank will be likely (as with segregated waste storage), it is easier to modify a horizontal tank.

Installation and maintenance of aboveground tanks are less troublesome than for underground tanks. With underground storage, the functions of gaging, pumping, and leak detection become more difficult. With storage of hazardous wastes and liquids, underground tanks and their possibility of leakage is discouraged. Underground tanks lend themselves to accelerated corrosion and often require cathodic protection. Also, a means of containing leaked or spilled materials is necessary for most underground tanks. However, when very volatile materials are stored, underground storage is the only practical alternative.

Depending upon the liquid waste contained, tank storage can also require many accessory equipment features such as:

(1) Flash arrester fill pipes.

(2) Flame arrester rodding and sampling units.

(3) Conservation breather vents with pipe-away construction--used where pressure or vacuum relief is required and vapors must be piped away rather than released into the atmosphere.

(4) Tank vent condensers--designed to condense and return to the tank vapors that could escape, as shown in Figure 5-18. Due to potential unanticipated reactions between physically or chemically incompatible wastes, large volumes of organic vapor can be generated and must be vented to some control device. Venting the tanks into the incinerator combustion air intake has the potential of creating an explosive condition, even with nitrogen blanketing. Chilled water condensers, coupled with knockout tanks, are best utilized to control emissions from the liquid transfer and storage facilities [17].

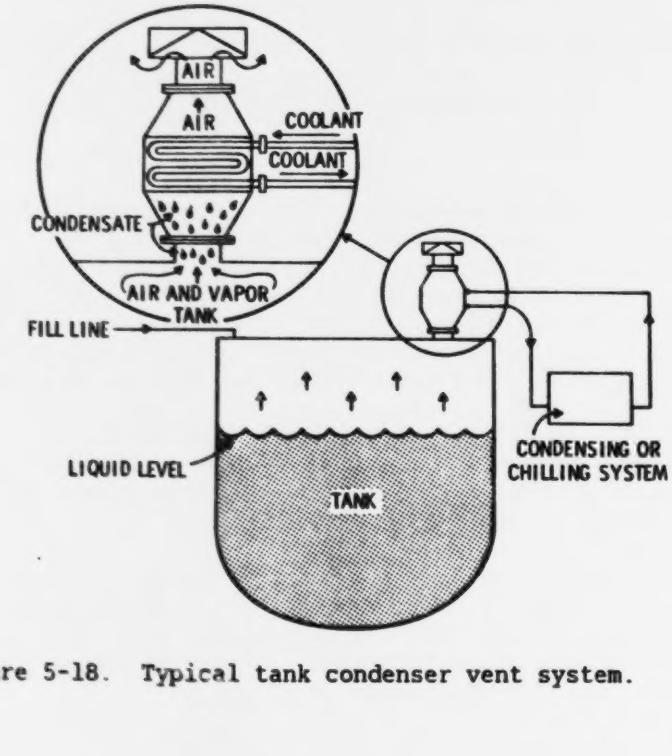


Figure 5-18. Typical tank condenser vent system.

(5) Steam-heated conservation, pressure, or vacuum relief vents--designed for use on tanks containing liquids whose vapors tend to crystallize at ambient temperatures (also with pipe-away construction).

(6) Mushroom vent with flame arrester--used where it is not necessary to conserve vapor losses, but where low flash point solvent materials must be protected against fire and explosion from exterior sources of ignition.

(7) Steam-jacketed flame arrester vents--designed for use on tanks containing hazardous liquids whose characteristics require steam heating to prevent crystallization of interior vapors; e.g., naphthalene.

(8) Manhole and emergency pressure relief vent covers--to provide emergency pressure relief as well as access for tank cleaning.

(9) Internal safety valve--intended for use where tanks are required to be equipped with valves that close automatically when subjected to fire.

(10) Integral internal heating coils--usually steam, designed to prevent freezing of tank contents.

(11) Overflow piping--usually connected to an adjacent tank to mitigate spill possibilities.

5.4.1.2 Bulk Solids Storage--

Material received as bulk solids at a hazardous waste incineration facility can be stored in three ways:

(1) Enclosed bins or silos

(2) Concrete pits or below-grade concrete hoppers

(3) Stockpiles

Generally, solid hazardous waste materials which present a toxicity problem to plant personnel are stored in totally-enclosed storage, such as single-outlet bins, multiple-outlet silos, and portable bins. These enclosures protect the hazardous material from exposure to the elements, or guard against dangers represented by explosive, flammable, ignitable, or corrosive properties. Table 5-3 gives a rough rating of the major types of bulk storage units in terms of their capacities and method of reclamation or discharge.

Multiple-Outlet Silos--Multiple-outlet silos are useful for storing small or medium quantities of material. Because they generally rely on gravity flow to discharge the solids, hopper slopes and outlet dimensions must satisfy the minimum requirements for uninhibited flow.

One of the most common problems with multiple-outlet silos is structural failure caused by nonsymmetric flow patterns. Side discharge is typically used with free-flowing materials such as grain. With this arrangement, bin failures, especially in steel structures, manifest themselves as dents in the region of the localized flow channel.

TABLE 5-3. TYPES AND CHARACTERISTICS OF DRY BULK STORAGE [13]

Storage technique and method of reclaim or discharge	Storage capacity		
	Small, under 20,000 ft^3	Med.	Large, over 700,000 ft^3
Stockpiles			
Bottom tunnel		X	X
Bucket wheel			X
Scraper truck			X
Front-end loader	X	X	
Multiple-outlet silos			
Mass flow	X	X	
Expanded flow	X	X	
Funnel flow	X	X	
Single-outlet bins			
Mass flow	X		
Expanded flow	X	X	
Funnel flow	X	X	
Portable bins			
Funnel flow	X		
Mass flow	X		
Concrete pits			
Grapple	X	X	

Single-Outlet Bins--Single-outlet bins are the most common type of storage units in industry. Most of them are funnel-flow type, in which the sidewalls of the hopper are sufficiently steep to maintain continuous flow. Most pyramidal hoppers and conical hoppers with slopes of 60° or less from the horizontal will display funnel flow.

Portable Bins--These special bulk units, generally limited to volumes less than 200 ft^3, are often thought of simply as large buckets used to transport homogenous material of a specified size and composition. Typically, these bins are cube-shaped, with a flat hopper leading to a central outlet about 10 in. or less in diameter.

Some of the solid material characteristics considered when designing a solids storage and retrieval system include:

(1) Bulk density
(2) Moisture content
(3) Particle size
(4) Angle of repose

(5) Angle of slide
(6) Temperature
(7) Pressure differentials
(8) Abrasiveness
(9) Cohesiveness
(10) Material melting point
(11) Hygroscopicity

Many different types of bin hopper discharging devices have been developed, primarily because solid material retrieval is difficult to achieve reliably and consistently. Some of the bin hopper discharging devices are:

(1) Manual prodding through poke holes to eliminate material "bridging" (definitely not useful for hazardous wastes)
(2) Chain or cable elements suspended to reduce bridging
(3) Agitators or "rotating fingers"
(4) Sweep arms or rotary vanes
(5) Rotary plows
(6) Multiple screw bottoms
(7) Bin activators or vibratory sections
(8) Electromechanical devices, such as side vibrators
(9) Pneumatic and hydraulic vibrators
(10) Air pads, cushions, and slides, wherein air is injected to fluidize the material.

If one word could describe the basis of all solids retrieval problems, it would be "friction." Any hopper surface which can reduce friction can minimize bridging or arching. Fortunately, for a corrosive-type hazardous solid material, the material of construction or lining of the hopper bin can solve a dual problem. Materials to be given consideration are:

(1) Stainless steel, full thickness or clad-polished
(2) Teflon sheets bonded to steel containers.

Items of safety in bin design considerations include:

(1) Access doors for inspection, routine maintenance, and firefighting
(2) Fire detection--sensors; alarming; automatic suppression systems such as CO_2, foam, or water; standpipes for connection to a water source and availability of fire hoses
(3) Detection of level and pluggage
(4) Provisions for dust control
(5) Provisions for maintenance removal of bin discharge mechanisms which are normally buried under waste.

Concrete Waste Pits--Concrete solid waste pits are in wide use in municipal and industrial waste disposal plants which handle nonhazardous wastes. Bulk solid refuse is dumped into the storage pit by packer truck, load lugger bucket, or other collection vehicles.

The storage pits are normally under an enclosure to prevent precipitation from entering, and there is an approximately 10 ft wide vestibule which trucks back into. Refuse is picked out of the pit by a bridge crane with a bucket or grapple, and the crane delivers the solid waste to an infeed system. Control of the crane and grapple is usually from an air-conditioned pulpit in which the operator sits. Control is a saturable reactor type which provides cushioned starting and acceleration. Protective zones are provided preventing the operator from drawing the grapple into a wall, pulpit, etc. Automatic control can be provided.

For fugitive dust control at each truck dumping point, there can be a down blast heater. The vestibule and pit area are designed for complete sprinkler protection of fire. Sprays in both the front and rear wall of the pit can be included to suppress dust clouds that arise when a load is dumped.

The entire pit is usually watertight and sloped to troughs and drains for dewatering. When a pit is constructed below grade, it is usually necessary to have a sump. Screening devices to prevent material from entering the sump are also used [18].

Stockpiles--Hazardous wastes are occasionally stored in piles, generally small in size. Many are in buldings or maintained outside, under cover, on concrete or other pads. They are most frequently used to accumulate waste composed of a single, dry material.

Wind dispersal is controlled by a cover or windscreen; piles inside a building are adequately protected from dispersal.

5.4.1.3 Container Storage--
Hazardous materials for incineration will often arrive in small container form (e.g., 55 gallon drums), and can be stored until used, provided the containers are in good condition and are not leaking.

Metal and fiber containers are loaded, stored, and unloaded so as to minimize the possibility of container damage. The containers are stored in a covered area, off the ground, in a manner which will preclude damage, weathering, and subsequent leakage. Storage pads of concrete or other impervious materials are used as a base to prevent ground water leaching and percolation. The area itself is provided for drainage to a treatment facility in an analogous manner to diked storage tank areas.

If some containers contain corrosive substances, these are stored so that, should leakage develop during storage, these substances will not corrode through adjacent containers. Waste segregation practices of bulk storage (liquid and solid) also prevail with indoor container storage.

All containers in storage are inspected to insure physical and mechanical integrity, and the drainage and containment systems are also inspected.

Nonstationary containers can proliferate in a storage area; hence, all containers are clearly labeled and records maintained. In this way the operator is able to quickly locate any hazardous waste.

Waste containers are sealed to prevent the escape of vapors. Gasketed closures of containers and containers themselves are normally of a material that will not be deteriorated by the waste inside the container. The container storage enclosure area is vented to allow for collection and control of any released vapors.

5.4.1.4 Tank Cars--

Hazardous waste storage can also occur in parked tank cars -- both truck and rail. Usually, the wastes are then pumped directly to the incinerator or blending tanks. As with bulk storage, the area is designed to prevent ground contamination and percolation, and diked or drained to collect spills and surface runoff. As with container storage, each tank car is clearly labeled and records maintained to quickly locate each hazardous waste.

5.4.2 Segregation of Wastes During Storage

Hazardous wastes may be segregated at an incineration facility due to waste categories for fuel value and are certain to be segregated when incompatible waste types are received. The type of incinerator and nature of wastes which can be burned will greatly influence the extent of waste segregation during storage.

Incompatible wastes are normally segregated due to corrosive and reactive effects. Examples of segregation during storage are reactive chemicals which should be stored in air or water tight containers, oxidizers which should be isolated from flammable materials, and materials which may polymerize in the presence of accelerators. Section 5.5 on waste blending contains a ready and quick reference for determining the compatibility reactions of most binary combinations of hazardous wastes.

Wastes may also be segregated and stored to allow for fuel blending for maximal incinerator performance. Examples of the categorization of wastes which could occur and the storage requirements necessary are as follows [19]:

(1) Light hydrocarbons and nonaqueous solvents -- includes low flash point wastes such as paint thinners, aromatics (toluene, benzene, xylene, etc.) which reduce viscosity of heavier wastes and assist fuel oil in initial heating prior to firing heavy blends.

(2) Medium to heavyweight hydrocarbons -- includes still bottom residues, crankcase oils, and discarded transformer oils. Most have high flash points but relatively low ignition temperatures and moisture is generally under 10 percent. Handling these wastes may require use of insulated storage tanks and auxiliary heat to maintain proper fluidity, particularly during cold weather.

(3) Low-water-content aqueous wastes -- sludges from fatty acids production, starches, reject fatty acids, waste soluble oils, and clabberstock. These wastes may be blended in limited proportions with the heavier wastes in group 2 but require storage in insulated and heated tanks to avoid congealing and freezing of contained water during winter.

(4) Dirty solvents -- includes kerosene, soluble inks, oil-solvent residues, organic pigments. Storage tanks do not require insulation or heating.

(5) High-water-content aqueous wastes, semisolids, sludges, and low heating value liquids -- includes aqueous mixture of paint, enamel and lacquer oversprays, liquid polymers in water, paint sludges.

(6) Skimmings from wastewater treatment plants -- floatable material skimmed from settling tanks and thickeners such as spent grease.

(7) Spent earth -- from filters and contaminated areas. Due to high water content this waste can require insulated storage, auxiliary heat, and continuous agitation to maintain fluidity and prevent freezing in cold weather.

5.4.3 Safety Provisions for Storage Areas

For safe facility design in the storage area, provisions are made to protect personnel and the immediate environment from catastrophe--particularly fire hazards and material spills. Liquid and container storage are most likely to occur at a hazardous waste incineration facility, and are discussed below.

5.4.3.1 Fire Safety--

Volume 1 of National Fire Codes (National Fire Protection Association (NFPA), Boston) contains recommendations and standards in NFPA 30, "Flammable and Combustible Liquids Code," for venting, drainage, and dike construction of tanks for flammable liquids. Also possibly applicable are NFPA 327, "Standard Procedures for Cleaning or Safeguarding Small Tanks and Containers", and NFPA 43A, "Liquid and Solid Oxidizing Materials."

Many of the devices and equipment utilized to prevent fire hazards in the liquid storage area were discussed in Section 5.4.1.1. Some other considerations which apply to storage of large quantities of flammable liquids include:

(1) Instrumentation or remotely-operated valves to minimize flow of flammables.

(2) Combustible gas monitors in the storage area which have an alarm set below the lower flammable limit.

(3) Combustible gas monitors that automatically actuate a deluge system or safely shut down systems below lower flammable limit.

(4) Drainage and collection ponds (equalization basin) to carry away liquid spills resulting from a fire incident.

For the storage of drums, many safety precautions can be used for the protection of the operators who open and inspect drums prior to incineration. Safety features include:

(1) explosion-proof electrical equipment
(2) automatic fire doors
(3) a "light water" system
(4) dry chemical and CO_2 fire extinguishers
(5) special safety fork trucks with nonsparking forks
(6) air-operated pumps
(7) nonsparking tools
(8) safety showers and eyewashes
(9) safety glasses and face shields
(10) a ventilation system which makes a minimum of three air volume changes per hour in all areas and thirteen (13) air volume changes per hour in the drum pumping room or area.

For storage of bulk-solids, evidence of spontaneous heating is closely monitored. Heat-sensitive devices in silos and bins are installed, connected to a continuous temperature recorder at a central control board and arranged to sound an alarm if unsafe temperatures are produced. Excessively wet materials are not placed or permitted in storage silos or bins.

5.4.3.2 Spill/Toxicity Safety--

The most effective way of addressing a bulk liquid storage area's vulnerability to spill incidents is to prevent them from happening. Assuming that all storage tanks are properly designed, equipped with overflow alarms, and used only for intended or compatible purposes, the possibility of spills can be substantially reduced by:

- Assuring the continual physical integrity of the vessels and their fittings (inspection and testing).

- Establishing strong administrative controls covering all loading/unloading and in-plant transfer operations (plans and procedures).

- Providing adequate secondary containment facilities (dikes, diversion ditches, equalization basins).

Physical Testing and Inspections--Spark testing (of lined storage tanks), wall-thickness testing, or other appropriate means of nondestructive physical testing or inspection are conducted on storage vessels which hold hazardous liquids.

The exterior of each bulk storage tank is also visually examined at regular intervals. Each inspection includes an examination of seams, rivets, nozzle connections, valves, and pipelines directly connected to the tank. Visible leaks of waste from tank seams and rivets are then promptly corrected. Foundations and/or tank supports are also subject to inspection.

New and old tank installations are, as far as practical, fail-safe engineered or updated to a fail-safe engineered installation. Design considerations are given to providing the following devices:

(a) High liquid-level bell or horn alarms with an audio signal at a constantly manned operating or listening station; in smaller plants an audible air vent may suffice.

(b) Low liquid-level alarms with an audio signal at a constantly manned operation or listening station; such alarms can also have a non-bypassing reset device that can be readjusted to a given operating level following tank fill or liquid removal.

(c) High liquid-level pump cutoff devices set to stop flow at a predetermined tank content level.

(d) Direct audible or code signal communication between the tank gauger and the pumping station.

(e) At least one fast response system for determining the liquid level of each bulk storage tank such as digital computers, telepulse, or direct vision gauges.

Tanks are then not knowingly used if the "head" or "top" is in a corroded-through condition. Action is taken to drain such tanks and repair the defective member as promptly as possible.

Partially buried tanks for the storage of oil or hazardous materials are normally avoided, unless the buried section of the shell is adequately coated to prevent rapid corrosion of metallic surfaces buried in damp earth, especially at the earth/air interface.

Buried storage tanks represent a potential for undetected spills. A buried installation, when required, is wrapped and coated to retard corrosive action. In addition, the earth is subjected to electrolytic testing to determine if the tank should be further shielded by a cathodic protection system. Such buried tanks are also subjected to regular hydrostatic testing. In lieu of the above, arrangements can be made to expose the outer shell of the tank for external examination at least every five years. Alternatively, a means of conducting examinations of the tank at regular intervals can be provided, e.g., down-hole television.

Tank Overfill--A variety of engineering practices suited to the nature of any hazardous material stored are used to prevent tank overfilling, a major source of spill incidents. The following general principles can be used in designing a system of protection against tank overfill:

(1) Tanks are gauged before filling.
(2) Overflow pipes are connected to adjacent, compatable waste storage tanks, or to secondary containment.
(3) Fail-safe devices and level alarms have been tested and insured in place.
(4) Provisions to prevent static electricity discharge have been implemented.

Protection of Integral Heating Coils--Many liquids in storage require auxiliary heating to remain in a fluid state. This is normally accomplished economically by integral steam coils inside the storage tank and, often, agitation.

To control leakage through integral heating coils which may become defective through prolonged use, the following design factors are considered and applied:

(1) The past life span of internal steam coils is determined, and a regular system of maintenance and replacement that does not exceed the anticipated life span is established.

(2) The temperature and environment is carefully considered when selecting heating coil materials to reduce failure from corrosive action, prolong life, and reduce replacement costs.

(3) The steam return of exhaust lines from integral heating coils which discharge into an open watercourse is monitored for contamination, or passed through a settling tank, or skimmer, etc.

(4) The nature of the wastes is carefully considered to prevent wastes from caking on the heating coils, which reduces their efficiency as well as causing waste materials to be contained in a tank thought to be empty.

(5) The feasibility of installing an external heating system is also considered, and, if feasible, often is recommended to solve problems which may arise from implementation of (1) through (4).

Secondary Containment--All bulk storage tank installations at a hazardous waste incineration facility are planned so that a secondary means of containment is provided for the entire contents of the largest single tank. Dikes, containment curbs, and pits are commonly employed for this purpose, but they may not always be appropriate. An alternative system would consist of a complete drainage trench enclosure arranged so that a spill could collect and be safely confined in an in-plant catchment basin or holding pond.

Dikes are generally constructed of concrete, cinder blocks, and/or earth. However, dike materials are designed to be chemially resistant and essentially impervious (e.g., permeability rate no greater than 10^{-7} cm/s when subjected to a head of 1 ft of water) to the substances contained. Acceptable engineering design criteria for a dike will enable it to withstand a sudden massive release.

Some of the important design guidelines for dike construction include [20]:

(1) Single storage tank -- The capacity of diked area is at least adequate to hold the entire tank contents plus a reasonable allowance for precipitation. Local regulations may contain more stringent requirements. An alternative design goal is for the diked area to contain the volume of the tank plus 1 ft of freeboard.

(2) Clustered storage tanks -- The capacity of the diked area is adequate to hold the entire contents of the largest tank plus a reasonable allowance for precipitation. Again, local regulations may be more stringent.

(3) To the extent feasible, dike walls generally do not exceed a height of 6 ft above interior grade. A greater height might require the observance of tank entry procedures including safety harnesses, oxygen deficiency checks, standby observers, and other precautions each time it is necessary to enter the diked area.

(4) For earthen dikes, a slop of 2.5:1 is preferred. Earthen dike walls 3 ft or more in height are generally designed with a flat walkway section at the top not less than 2 ft wide.

(5) Dikes may also need to be constructed to provide necessary ramps for vehicles needing access to the storage areas.

(6) The disposal of rainwater and other liquids from within diked areas is normally accomplished by a manually activated pump or siphon system. Such accumulated stormwater must be removed in order to maintain adequate volume for a maximum spill. Figure 5-19 shows a diversion structure which serves this purpose. Of course, retained drawoff water and the rainfall accumulated are checked (analyzed) before release.

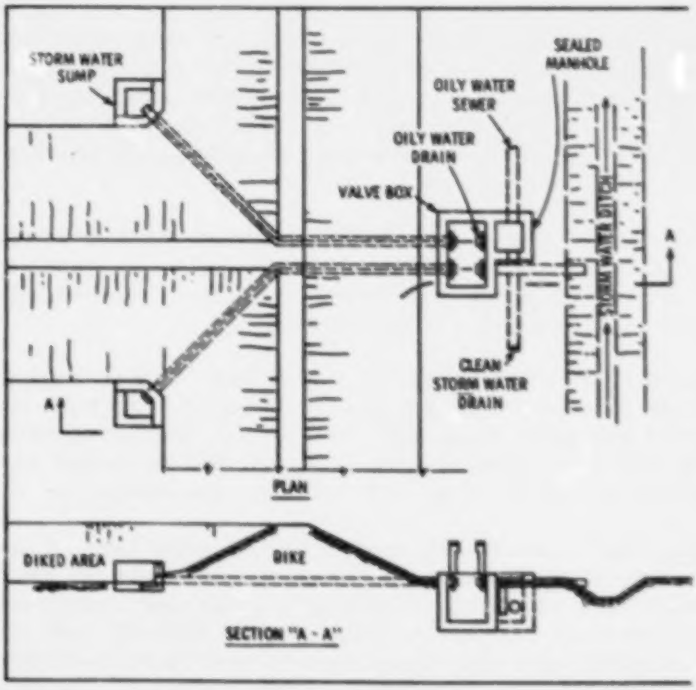

STORM WATER SUMP
SEALED MANHOLE
OILY WATER SEWER
OILY WATER DRAIN
VALVE BOX
STORM WATER DITCH
A
CLEAN STORM WATER DRAIN
A
PLAN
DIKED AREA
DIKE
SECTION "A - A"

Figure 5-19. Dike drain detail Type "A" diversion box [21].

(7) For hazardous and toxic liquids, the ground area within the dike and curbing are designed to be essentially impermeable. This can be achieved by use of concrete, asphalt, or suitable clays. Neutralizing materials for the stored chemical waste such as limestone or clam shells for acidic wastes are sometimes used as a ground cover, although neutralizing ground covers need to be replaced promptly after a spill or incident.

(8) Generally, it is recommended that there be no discharge or loading pipes through the dike wall. However, construction design has to conform to state and local regulation, and some local fire regulations (applicable to flammable liquids) require a valved pipe through the dike wall, while others prohibit this installation. If a drainage valve through the dike wall is required, it is kept locked in the closed position when not in use and a chemically resistant seal is installed around the pipe passing through the wall.

(9) The storage tanks located immediately adjacent to the dike itself are oriented so that no manholes face the dike. This is considered desirable, so that, if a manhole fails, the resulting discharge from a full tank will not be aimed over or at the dike. Where this design is not feasible, appropriate baffles are installed to deflect potential leaks and cause them to drop within the contained area.

(10) If storage tanks located immediately adjacent to the dike are equipped with fill lines which enter the tank near the bottom, and if the fluid pumped has suspended abrasive material, the discharge into the tank should be on the dike side, discharging against the tank side away from the dike. Alternatively, a baffle plate located inside the tank opposite the pump discharge in the area apt to be abraded, may be provided.

The final defense in the prevention and containment of liquid and solid spills is at the end of the plant storm-drain system. Here, an automatic system monitors the storm drain for acidity or alkalinity (pH), turbidity, total oxygen demand (TOD), and flow (variance from normal).

If any of the parameters are sensed beyond normal limits, a diversion gate automatically move into position to divert the discharge to a holding pond. Such a system provides protection against a spill that goes beyond the process area, dikes, and into the storm drains. Discharges diverted to the holding pond are removed to a process area for recycle, treatment, or disposal.

Container Storage--Containers with a capacity of less than 45 gallons are stored out-of-doors, when possible, in rows no more than 30 feet in length, five feet in width, and six feet in height. Containers which have a capacity of 45 gallons or more are stored in rows no more than 30 feet in length and two containers in width and should not be stacked. A minimum of five feet between rows of containers of hazardous wastes is usually maintained.

If exposure of the containers to moisture or direct sunlight (see Section 5.5) will create a hazardous condition or adversely affect the containers' ability to hold the hazardous waste, the containers are then stored in an area with overhead roofing or other covering that does not obstruct the visibility of the container labels.

The area under or around the container storage area is built to be able to collect or hold any spilled material; e.g., collection drains, trenches, or dikes.

5.5 WASTE BLENDING AND/OR PROCESSING BEFORE INCINERATION

The methods by which hazardous wastes are removed from storage, prepared for incineration, and fed to the incinerator are dependent on the nature of the waste and type of incinerator. Figure 5-4 in Section 5.3 illustrates the various pathways from storage to final feed into the incinerator. Careful design consideration is given:

(a) To the layout for liquid waste blending, pumping and associated pipework, and

(b) To the handling and feeding arrangements for nonpumpable sludges, solids, and containerized wastes, where applicable.

Operating experience has shown that these are areas that do not receive as much attention as is necessary; the overall success of an incineration facility depends upon the successful integration of storage, feeding, and firing equipment.

5.5.1 Waste Compatibilities

The "combination of wastes" often presents many problems for the management of hazardous wastes. In some instances, the combination or mixture of two or more types of the wastes produces undesirable or uncontrolled reactions resulting in adverse consequences. These reactions may cause any one or more of the following:

(1) Heat generation, fire, and/or explosions,
(2) Formation of toxic fumes,
(3) Formation of flammable gases,
(4) Volatilization of toxic or flammable substances,
(5) Formation of substances of greater toxicity,
(6) Formation of shock and friction sensitive compounds,
(7) Pressurization in closed vessels,
(8) Solubilization of toxic substances,
(9) Dispersal of toxic dusts, mists, and particles, and
(10) Violent polymerization.

Available data indicate that hazardous wastes are ill-defined, complex mixtures generated by a great variety of sources. No two types of wastes appear to be identical, for even a single process appears to produce different types of wastes. Characterization of the wastes by the analysis of the processes and the materials used appear to give inaccurate descriptions of the resulting wastes. The data indicate that each waste is unique and that individual reactivities may be best assessed by identifying respective chemical constituents.

For further information on compatability of hazardous waste refer to the Guidance Manual entitled, "Treatment Trial Tests and Hazardous Waste Compatability". Another commonly used laboratory test for waste compatibility is ASTM E476-73, "Thermal Instability of Confined Condensed Phase Systems," which measures the temperature at which exothermic reactions begin and amount of pressure release.

While empirical data exist concerning the consequences of reactions between pure substances under laboratory conditions (mostly binary combinations), very little work has been done in the field of waste combination reactions. Very seldom are wastes pure substances. They are usually sludges, emulsions, suspensions, or slurries containing many different compounds.

The chance of combining noncompatible wastes within a specific category can be minimized in several ways. First, the problem is restricted to pumpable wastes since nonpumpable scrap is often handled in individual drums or bin containers and is not mixed prior to incineration. Secondly, a single manufacturing location normally uses compatible solvents. Thus, with knowledge of the generator in hand (manifest system), the greatest chance that noncompatible wastes will be combined occurs at the incineration facility. Basically, proper labelling at the waste generation source and the experience and knowledge in liquid segregation of the incinerator operators will greatly minimize the problem. The primary concern in waste blending is minimizing the reactivity of combined wastes. Other secondary concerns in waste blending are precipitate formation, increases in viscosity, and blends which could generate acid gas combustion products.

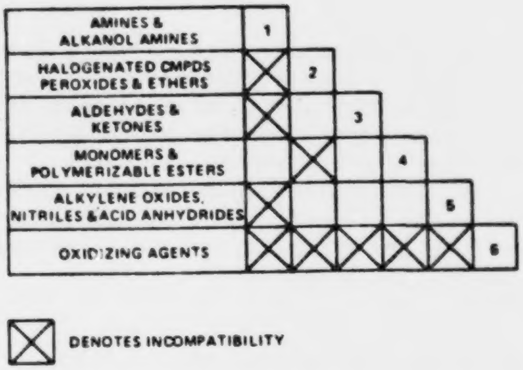
It is evident from the existing data that the largest and most common dangers inherent from incompatible reactions involve strong acids or bases. For this reason, it is desirable that acids and bases be neutralized to within a pH range of 4.5 to 9 before being mixed with other wastes (sometimes acidic and basic wastes are mixed in a controlled manner to achieve pH neutrality). Even within this restricted pH range, acids should be segregated from acid-soluble sulfide and cyanide salts.

With the above inclusions, an example of a compatibility matrix is depicted in Figures 5-20 and 5-21. If it is not feasible to neutralize acid wastes and/or caustics to within the prescribed pH range, then the matrix in Figure 5-21 is used.

5.5.2 Liquid Feed and Blending Equipment

Liquid blending or mixing of hazardous wastes is done as part of an overall liquid feed system, which includes a feed pump, usually some recirculation to the mix vessel, and associated piping to the incinerator.

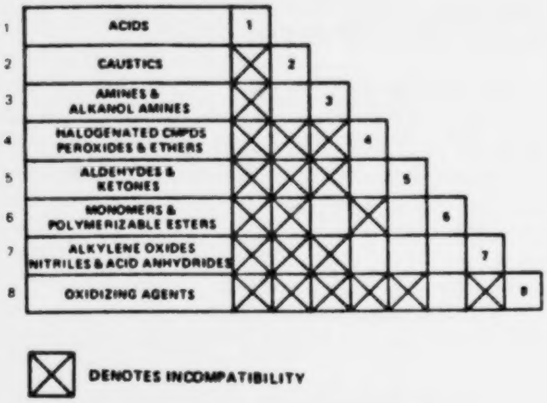
An example of a mixing vessel is shown in Figure 5-22. For hazardous waste blending, the vessel is always closed-top rather than open-top to prevent



AMINES & ALKANOL AMINES	1					
HALOGENATED CMPDS PEROXIDES & ETHERS	☒	2				
ALDEHYDES & KETONES	☒		3			
MONOMERS & POLYMERIZABLE ESTERS		☒		4		
ALKYLENE OXIDES, NITRILES & ACID ANHYDRIDES	☒				5	
OXIDIZING AGENTS	☒	☒	☒	☒	☒	6

☒ DENOTES INCOMPATIBILITY

Figure 5-20. Compatibility matrix for neutralized hazardous wastes [1].



1	ACIDS	1							
2	CAUSTICS	☒	2						
3	AMINES & ALKANOL AMINES	☒		3					
4	HALOGENATED CMPDS PEROXIDES & ETHERS	☒	☒	☒	4				
5	ALDEHYDES & KETONES	☒	☒	☒		5			
6	MONOMERS & POLYMERIZABLE ESTERS	☒	☒		☒		6		
7	ALKYLENE OXIDES NITRILES & ACID ANHYDRIDES	☒	☒	☒				7	
8	OXIDIZING AGENTS	☒	☒	☒	☒	☒		☒	8

☒ DENOTES INCOMPATIBILITY

Figure 5-21. Compatibility matrix when wastes cannot be neutralized [1].

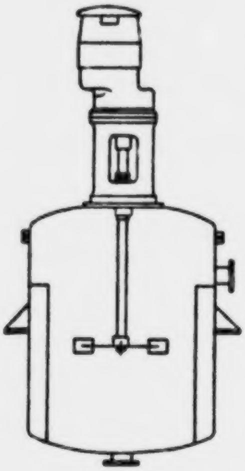


Figure 5-22. Example of a baffled mixing vessel [14].

splashing and vapor escape. Impeller mixer drives, both direct drive and gear drive, are available. The shaft length and number or configuration of impellers must be based on the geometry of the tank and viscosities of the waste. Generally, fuel blending requires a mild agitation or intensity of blending, and the use of baffles increases the turbulence and mixing characteristics.

Where conditions warrant extreme safety, the blending and feeding process can be augmented by the use of a pneumatic compressed air (or gas mixer) motor and pneumatically-driven diaphram feed pump. The pumps used to transfer the wastes from storage to blending can also be pneumatic diaphram pumps. Inert gas blanketing with nitrogen of the mixing vessel is almost aways used. The blending tanks are also equipped with a pH recorder, an in-tank viscometer, and a sampling port and/or valve.

A typical sequence of activities prior to the injection of a liquid waste blend to the incinerator is as follows: a waste batch arrives at the plant; a grab sample is taken to confirm that the shipment is within the contracted specifications between the generator and the incinerator operator; the waste batch is then unloaded and received in an agitated tank to homogenize the batch; an integrated sample is taken and analyzed for Btu content, ash content, chlorine content, etc., and the batch is then piped to the blending tank(s). If longer-term storage is necessary, the batches received are typically stored according to Btu content, ash content, or acid gas generating potential, as well as constraints dictated by waste compatibilities.

Waste blending goals are based on stack emissions limitations and loadings on the pollution control system. Worksheets 4-2 and 4-12 in Chapter 4 describe procedures for calculating the pollutant loadings of SO_2, acid gas components, and particulate matter. Ash contents of a waste blend are typically targeted at 1-1 1/2% in order to meet particulate emission limitations; if a chlorinated feed can be handled, the waste is blended to 15-30% chlorine; and a final Btu content of 7,000-9,000 Btu/lb is desirable (personal communication with Jerry Jordan, Rollins Environmental Services, Inc., Bridgeport, NJ, June 1981). The DRE requirement of 99.99% for the POHC's in the waste blend will have already been demonstrated in a trial burn or met through similarity criteria.

The amount of waste blended is usually enough for one day's operation of the incinerator.

If the type of incinerator can handle a slurry feed, the piping system should be designed to handle slurries. A slurry piping system has a minimum diameter of 4-6 times the particle size being pumped. All piping is recirculated to prevent settling, and possibly, mechanically comminuted to destroy any agglomerations which would cause plugging problems. A careful monitoring of the pump discharge pressure allows the operator to determine whether the feed pump is being influenced by the mixer (entrained air), as a check of slurry density, and to point to plugging problems. Figure 5-23 shows a slurry injection and monitoring system.

When slurries cannot be fed to an incinerator, the feed lines to the mixing tanks are filtered to prevent solids from reaching the burner nozzles. If slurries can be fed to the incinerator, sometimes an in-line grinder/chopper or grinder pump is used to reduce the size of the solids in the liquid waste.

Several stages of waste line filtering are advisable in order that control valves and measuring devices on the route to the burner nozzle do not stick or clog. In a waste mixture, solid particulate may form as precipitates or polymer seeds in situ. Frequently, the small beads may be elastomeric as behave in the same way as synthetic rubber by extruding through the screens. To minimize these conditions, stategically placed filters in sequence are very helpful in maintaining onstream time [15].

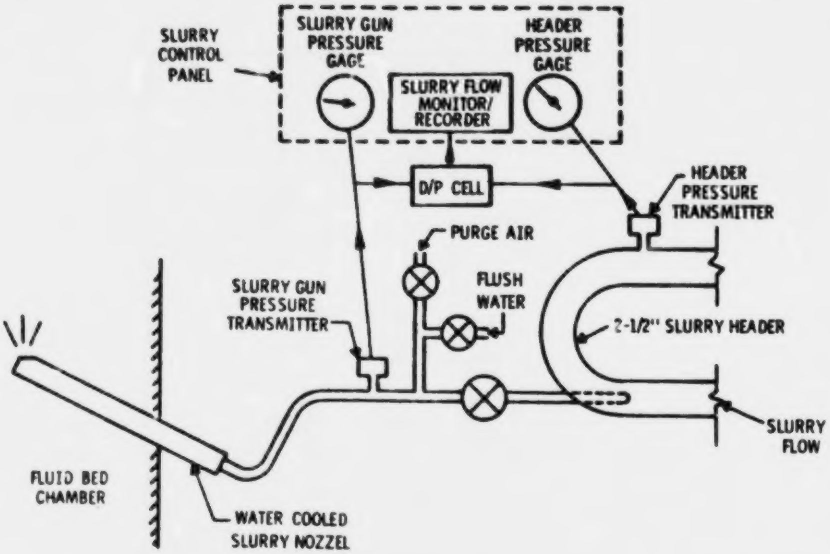

SLURRY CONTROL PANEL
SLURRY GUN PRESSURE GAGE
HEADER PRESSURE GAGE
SLURRY FLOW MONITOR/ RECORDER
D/P CELL
HEADER PRESSURE TRANSMITTER
PURGE AIR
FLUSH WATER
SLURRY GUN PRESSURE TRANSMITTER
2-1/2" SLURRY HEADER
SLURRY FLOW
FLUID BED CHAMBER
WATER COOLED SLURRY NOZZEL

Figure 5-23. Slurry injection and monitoring system.

Liquid streams can carry impurities of every sort. Furthermore, they may be highly viscous, which makes handling and atomizing difficult. Liquids should generally have a viscosity of 10,000 SSU or less to be satisfactorily pumped and handled in pipes. For atomization, a viscosity of 750 SSU is the maximum. Table 4-1 in Section 4.3.2 presents the viscosity and impurity limitations for various atomization techniques. Viscosity can usually be controlled by steam heating with tank coils or in-line heaters, but careful notice of the flash points must be taken. If preheating is not feasible, a lower viscosity and miscible liquid may be added to reduce the viscosity of the mixture. Line heat tracing is a must, taking into account worst case material freezing points and local winter design temperatures [15].

A feed system may have two or more recirculating loops installed, chiefly to keep any solids remaining in the liquid mixture from settling and plugging pipelines. Figure 5-24 illustrates an example of multiple recirculation.

5.5.3 Pumps and Piping

Pump and piping materials of construction are designed to be suitable for the liquids encountered (See Section 5.14). While centrifugal pumps can be used to feed liquids and/or slurries, positive displacement-type (PD) pumps are preferred. Unlike centrifugal pumps, they afford a reasonably tight shut-off and prevent siphoning when not in operation. Table 5-4 displays the materials of construction for positive displacement pumps. Figure 5-25 provides a pump classification chart.

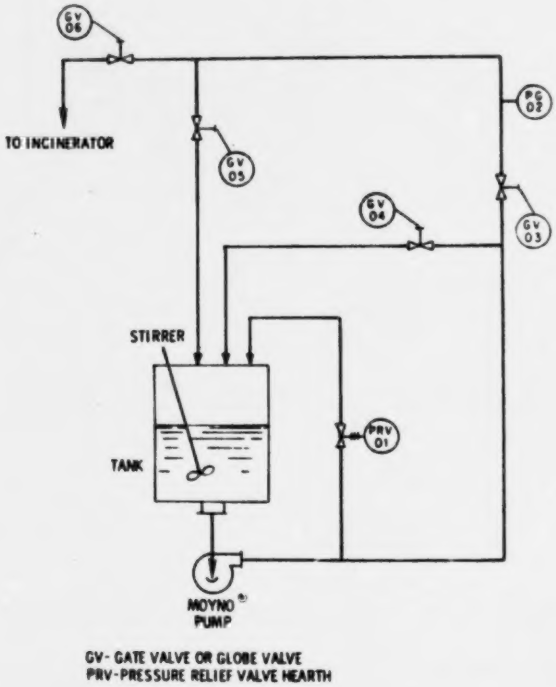

GV 06
TO INCINERATOR
GV 05
PG 02
GV 04
GV 03
STIRRER
TANK
PRV 01
MOYNO® PUMP
GV- GATE VALVE OR GLOBE VALVE
PRV-PRESSURE RELIEF VALVE HEARTH

Figure 5-24. Liquid feed system with redundant recirculation.

TABLE 5-4. MATERIALS OF CONSTRUCTION FOR POSITIVE DISPLACEMENT PUMPS

Plunger pump			Diaphragm pump
Pump body	Plunger	Lantern ring	Diaphragm or bellows
Steel	Stainless steel	Stainless steel	Elastometer
Iron	Ceramic	Allow 20	Teflon
Stainless steel	Monel	Hastelloy "C"	Polyethylene
PVC		PVC	Buna N
Alloy 20		Alumina-ceramic	Neoprene
Monel			Viton
Carpenter 20			Resistant steels

Check valves		
Valve body	Ball	Ball seat
Steel	Stainless steel	Stainless steel
Stainless steel	PVC	PVC
PVC	Hastelloy "C" to "D"	Alloy 20
Alloy 20	Alumina-ceramic	Monel
Hastelloy "C"		Hastelloy "C"
Monel		

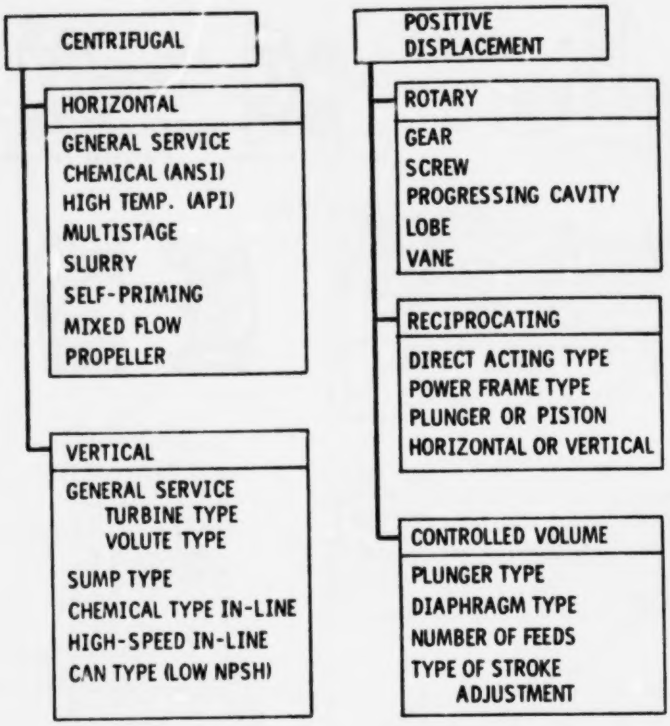

CENTRIFUGAL
HORIZONTAL
GENERAL SERVICE
CHEMICAL (ANSI)
HIGH TEMP. (API)
MULTISTAGE
SLURRY
SELF-PRIMING
MIXED FLOW
PROPELLER
VERTICAL
GENERAL SERVICE
TURBINE TYPE
VOLUTE TYPE
SUMP TYPE
CHEMICAL TYPE IN-LINE
HIGH-SPEED IN-LINE
CAN TYPE (LOW NPSH)
POSITIVE DISPLACEMENT
ROTARY
GEAR
SCREW
PROGRESSING CAVITY
LOBE
VANE
RECIPROCATING
DIRECT ACTING TYPE
POWER FRAME TYPE
PLUNGER OR PISTON
HORIZONTAL OR VERTICAL
CONTROLLED VOLUME
PLUNGER TYPE
DIAPHRAGM TYPE
NUMBER OF FEEDS
TYPE OF STROKE ADJUSTMENT

Figure 5-25. Pump classification chart.

A relief valve is usually provided downstream of PD pumps, of sufficient capacity to prevent excess pressure in the system. The relief valve discharge is then piped back to the supply source or to the suction side of the pump.

5.5.3.1 Positive-Displacement Pumps--
Positive-displacement pumps have as their principle of operation the displacement of the liquid from the pump case by reciprocating action of a piston or diaphragm, or rotating action of a gear, cam, vane, or screw. The type of action may be used to classify positive-displacement pumps as reciprocating or rotary. Figures 5-26 and 5-27 depict some typical pumps of each type. When a positive-displacement pump is stopped, it serves as a check valve to prevent backflow.

5.5.3.2 Centrifugal Pumps--
Centrifugal pumps operate by the principle of converting velocity pressure generated by centrifugal force to static pressure. Velocity is imparted to the fluid by an impeller that is rotated at high speeds. The fluid enters at the center of the impeller and is discharged from its periphery. Unlike positive-displacement pumps, when the centrifugal type of pump is stopped there is a tendency for the fluid to backflow. Figure 5-28 depicts some centrifugal pumps.

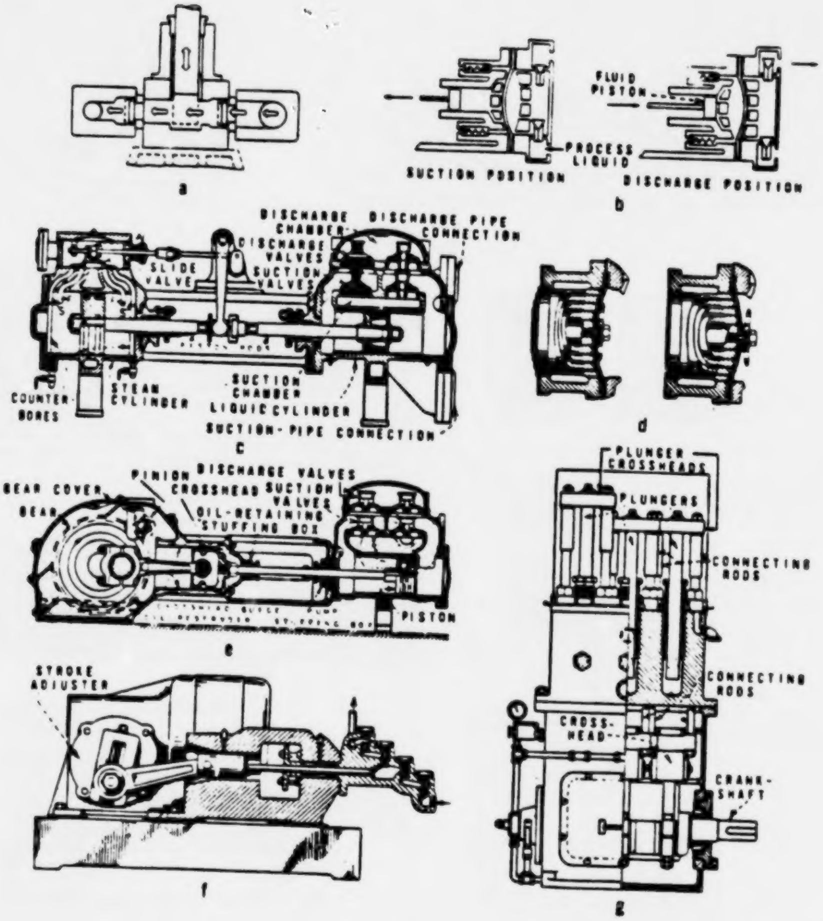

a
FLUID PISTON
PROCESS LIQUID
SUCTION POSITION
DISCHARGE POSITION
b
DISCHARGE CHAMBER
DISCHARGE PIPE CONNECTION
DISCHARGE VALVES
SLIDE VALVE
SUCTION VALVES
COUNTER-BORES
STEAM CYLINDER
SUCTION CHAMBER
LIQUID CYLINDER
SUCTION-PIPE CONNECTION
c
d
GEAR COVER
GEAR
PINION
DISCHARGE VALVES
CROSSHEAD
SUCTION VALVES
OIL-RETAINING STUFFING BOX
PISTON
e
STROKE ADJUSTER
f
PLUNGER CROSSHEADS
PLUNGERS
CONNECTING RODS
CONNECTING RODS
CROSS-HEAD
CRANK-SHAFT
g

Figure 5-26. Reciprocating pumps: (a) Principle of reciprocating pump, (b) principle of fluid-operated diaphragm pump, (c) direct-acting steam pump, (d) principle of mechanical diaphragm pump, (e) piston-type power pump, (f) plunger-type power pump with adjustable stroke, (g) inverted, vertical, triplex power pump [22].

Power for driving the various types of pumps is usually derived from electric motors or pneumatic drives. Most rotary pumps are driven by electric motor.

5.5.3.3 Pump Emission Control--

Operation of various pumps in the handling of fluids can result in the release of air contaminants. Both reciprocating and centrifugal pumps can be sources of emissions.

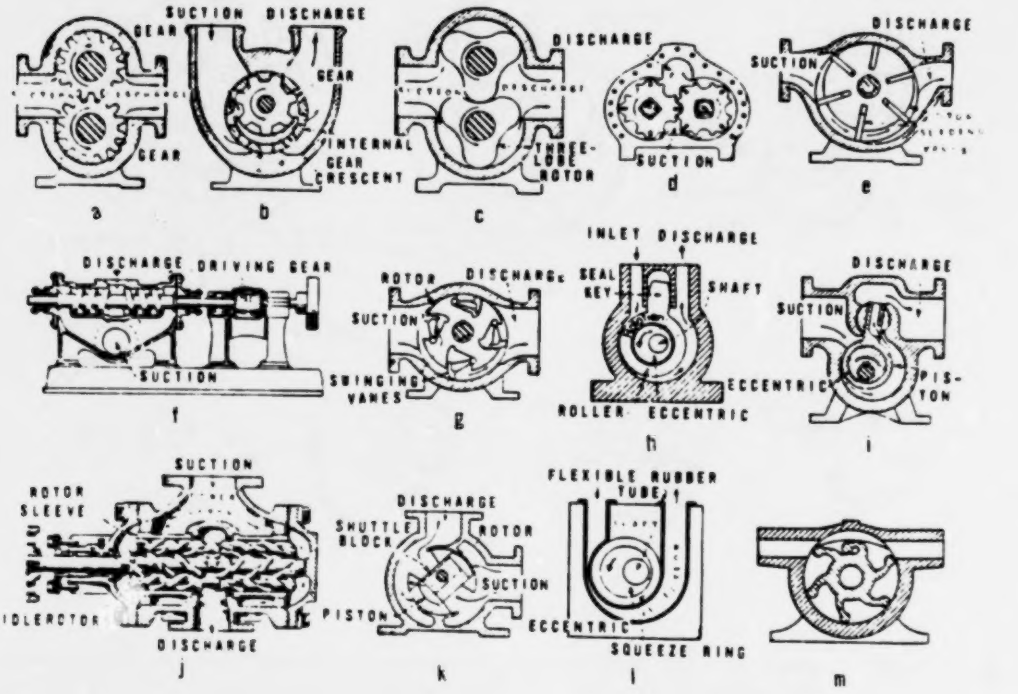

SUCTION
DISCHARGE
GEAR
GEAR
a
GEAR
INTERNAL GEAR
CRESCENT
b
DISCHARGE
THREE-LOBE ROTOR
c
SUCTION
d
DISCHARGE
SUCTION
e
DISCHARGE
DRIVING GEAR
SUCTION
f
ROTOR
DISCHARGE
SUCTION
SWINGING VANES
g
INLET
DISCHARGE
SEAL
KEY
SHAFT
ROLLER
ECCENTRIC
h
DISCHARGE
SUCTION
ECCENTRIC
PISTON
i
SUCTION
ROTOR SLEEVE
IDLEROTOR
DISCHARGE
j
DISCHARGE
SHUTTLE BLOCK
ROTOR
SUCTION
PISTON
k
FLEXIBLE RUBBER TUBE
ECCENTRIC
SQUEEZE RING
l
m

Figure 5-27. Rotary pumps: (a) External-gear pump, (b) internal-gear pump, (c) three-lobe pump, (d) four-lobe pump, (e) sliding-vane pump, (f) single-screw pump, (g) swinging-vane pump, (h) cam or roller pump, (i) cam-and-piston pump, (j) three-screw pump, (k) shuttle-block pump, (l) squeegee pump, (m) neoprene vane pump [22].

The opening in the cylinder or fluid end through which the connecting rod actuates the piston is the major potential source of containants from a reciprocating pump. In centrifugal pumps, normally the only potential source of leakage occurs where the drive shaft passes through the impeller casing.

Several means have been devised for sealing the annular clearance between pump shafts and fluid casings to retard leakage. For most applications, packed seals and mechanical seals are widely used.

Packed seals can be used on both positive displacement and centrifugal type pumps. Typical packed seals generally consist of a stuffing box filled with sealing material that encases the moving shaft. The stuffing box is fitted with a takeup ring that is made to compress the packing and cause it to tighten around the shaft. Materials used for packing vary with the fluid's temperature, physical and chemical properties, pressure, and pump type. Some commonly used materials are metal, rubber, leather, and plastics.

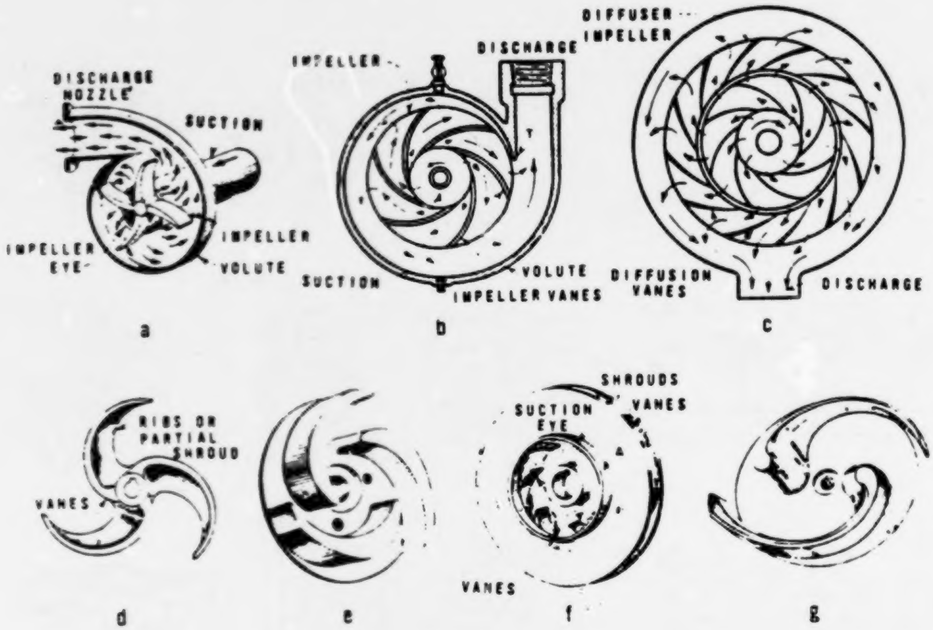

DISCHARGE NOZZLE
SUCTION
IMPELLER EYE
IMPELLER
VOLUTE
a
IMPELLER
DISCHARGE
SUCTION
VOLUTE
IMPELLER VANES
b
DIFFUSER
IMPELLER
DIFFUSION VANES
DISCHARGE
c
RIBS OR PARTIAL SHROUD
VANES
d
e
SHROUDS
VANES
SUCTION EYE
VANES
f
g

Figure 5-28. Centrifugal pumps: (a) Principle of centrifugal-type pump, (b) radial section through volute-type pump, (c) radial section through diffuser-type pump, (d) open impeller, (e) semi-enclosed impeller, (f) closed impeller, (g) nonclog impeller [22].

Lubrication of the contact surfaces of the packing and shaft is effected by a controlled amount of product leakage to the atmosphere. This feature makes packing seals undesirable in applications where the liquid can cause a pollution problem. The packing itself may also be saturated with some material such as graphite or oil that acts as a lubricant. In some cases cooling or quench water is used to cool the impeller shaft and the bearings.

The second commonly used means of sealing is the mechanical seal, which was developed over a period of years as a means of reducing leakage from pump glands. This type of seal can be used only in pumps that have a rotary shaft motion. A simple mechanical seal consists of two rings with wearing surfaces at right angles to the shaft. One ring is stationary while the other is attached to the shaft and rotates with it. A spring and the action of fluid pressure keep the two faces in contact. Lubrication of the wearing faces is accomplished by a thin film of the material being pumped. The wearing faces are precisely finished to ensure perfectly flat surfaces. Materials used in the manufacture of the sealing rings are many and varied. Choice of materials depends primarily upon properties of fluid being pumped, pressure, temperature, and speed of rotation. The vast majority of rotating faces in commercial use are made of carbon.

Emissions to the atmosphere from centrifugal pumps may be controlled in some cases by use of the described mechanical-type seals instead of packing glands. For cases not feasible to control with mechanical seals, specialized types of pumps, such as canned, diaphragm, or electromagnetic, are required.

Another specialty category is the sealed pump, which has no external seal or potential leakage. The two major types are the canned-rotor and the magnetic. Sealed pumps are used where no leakage can be tolerated, or where pump seal failure might cause major trouble. Such pumps are available in a limited range of sizes, most are low-flows, and all are of single- or two-stage construction. They have been used for both high-temperature and very low-temperature liquids. High-suction-pressure applications avoid the need for a troublesome high-pressure stuffing box. The centrifugal-type pumps follow the same hydraulic performance rules as conventional centrifugal pumps. Because of their small size, these pumps show a rather low efficiency but, in dangerous applications, efficiency must often be sacrificed for safety.

5.5.3.4 Pump and Piping Safety--
The primary objectives of pumping and piping systems are to prevent escape of liquid and to keep to a minimum the quantity lost if the liquid does escape. Inherent safety and freedom from human failure can, to a considerable extent, be built into a hazardous/flammable liquid system. Some design recommendations which help to attain the above objectives are listed below:

(1) Complete automatic sprinkler protection is provided in indoor areas where pumps, piping, tanks, and other parts of hazardous liquid transfer systems are located. In well-drained areas, sprinkler discharge of 0.30 gpm/sq ft of floor area is usually recommended to prevent structural and equipment damage.

(2) Indoor piping is located either overhead or in trenches in the floor. Overhead piping is normally installed close to ceilings or beams or along walls at least 6 ft above floor level. If piping is located in a trench in the floor, the trench is covered with removable steel plates and a trapped drain installed to a point of safe discharge. Positive-exhaust ventilation is provided in the trench, or the trench is backfilled with sand for liquids having closed-cup flash points below 110°F.

(3) Provisions are made to clean out the piping and equipment when long or scheduled shutdowns occur. This is usually done by purging with steam. The condensate is then collected and treated as a wastewater.

(4) Pipe materials are used which are chemically resistant to the liquid handled, which have adequate design strength to withstand the maximum service pressure and temperature, and which, when possible, are resistant to mechanical damage or thermal shock. Cast-iron, soft-rubber, or thermoplastic pipe or fittings of low melting point are never used.

(5) If corrosive liquids or high standards of purity make special pipe necessary, the use of stainless steel, nickel alloys, or other materials having high resistance to heat and mechanical damage or steel pipe with tin, glass, plastic, rubber, lead, or other lining is preferred to more fragile piping. If problems of corrosion, contaminations, or sanitation are the controlling factor, the use of carbon, graphite, glass, porcelain, thermosetting-plastic, or hard-rubber pipe is acceptable. Where specifically needed for the liquid being handled, aluminum alloy, aluminum bronze, or lead pipe is acceptable. Extra care is then used in locating, guarding, and supporting specialty piping against mechanical injury.

(6) Each waste material pipeline is clearly marked by lettering (coded or otherwise), color banding, or complete color coding to indicate the product transferred therein. The coding normally conforms with company policy or standard plant practice which, in turn, should conform with state or federal requirements.

(7) Each oil or hazardous material product-fill line which enters a tank below the liquid level has a one-way flow check valve located as closely as possible to the bulk storage tank. In addition to confining the product to the tank, in the event of valve or pipeline failure, the check valve permits overhaul of the main shut-off valve and should aid in preventing shock loading of the pipeline and valves from a "slug" of the tank content caused by backflow into an empty fill line. The waste feed flow in suction lines is controlled by use of a positive displacement pump.

(8) Buried pipelines are generally avoided. When they do occur however, buried installations have a protective wrapping and coating and are cathodically protected if soil conditions warrant. A section of the line is then exposed and inspected regularly. This action is normally recycled until the entire line has been exposed and examined on a regularly established frequency. An alternative would be the use of exposable pipe corridors or galleries.

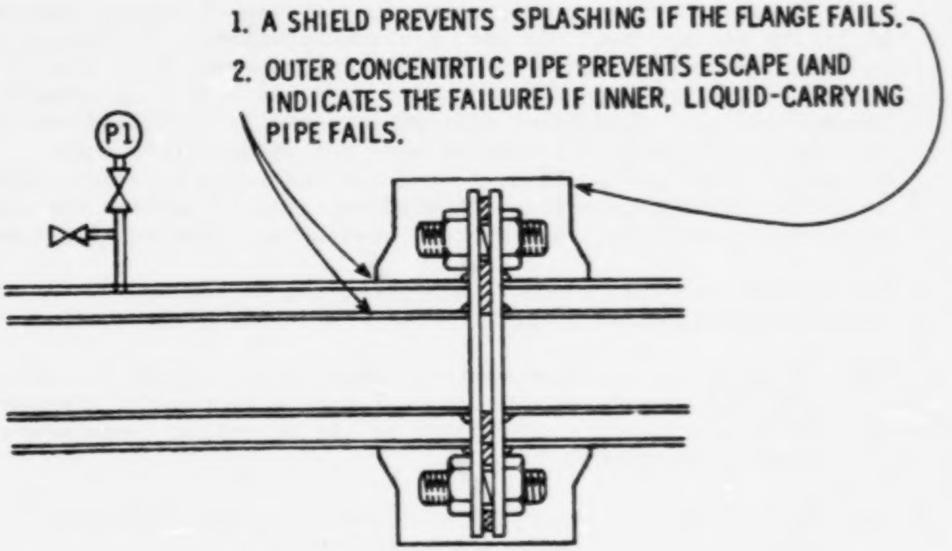
(9) When a pipeline is not in service, the terminal connection at the transfer point is capped or blank-flanged, and marked as to origin.

(10) Wood-to-metal is normally avoided as a pipeline support since it is apt to retain moisture and cause pipeline corrosion which, when coupled with the abrasive action caused by the pulsating action of the line, could cause line failure with resulting leakage. Supports are generally designed with only a minimum point of surface contact that allows for the pulsating movement (expansion and contraction) inspections at which time the general condition of items, such as flange joints, valve glands and bodies, catch trays, pipeline supports, locking of valves, and metal surfaces, are assessed.

(12) Elevated pipelines are also subjected to constant review to insure that the height of vehicular traffic granted plant entry does not exceed the lowermost height of the elevated line; gate check-in and in-plant travel are routes which warrant attention in this respect.

(13) Double-walled piping and/or flange shielding may be necessary for some above-ground pipelines carrying an especially hazardous or toxic waste stream if the pipeline intersects critical locations such as highways, driveways, railroads, or small watercourses. An example is illustrated in Figure 5-29.

(14) As far as practical, all pumps feeding the blender are located as close as possible to the storage tank.


1. A SHIELD PREVENTS SPLASHING IF THE FLANGE FAILS.

2. OUTER CONCENTRTIC PIPE PREVENTS ESCAPE (AND INDICATES THE FAILURE) IF INNER, LIQUID-CARRYING PIPE FAILS.

Figure 5-29. Two safeguards for piping of highly toxic liquids [23].

Many liquid wastes are solids at room temperature or become highly viscous at lower temperatures, and require heated piping to keep them in a fluid state suitable for transfer through the system. Liquids from heated tanks can usually be handled by providing adequate insulation on the pipe and fittings. The following methods of applying heat to piping systems are considered acceptable:

(1) Flammable-liquid lines are often steam-traced. The minimum steam pressure needed is used to make the liquid fluid, and a regulator is provided in the steam line with a relief valve downstream of the regulator set somewhat higher. The pipe and tracing are enclosed with noncombustible insulation.

(2) Electric heating cable is usually fastened along the pipe or wound spirally around it and the whole covered with noncombustible insulation. No splices in the cable should be made, and all connections are located outside the insulation-covered pipe. Individual thermostatic

controls for each cable section should be provided and protected with a fuse or fused disconnect switches of as low a rating as practical. Outdoors, weather-proof enclosures are provided for thermostats, plug assemblies, and switches, and in all installations are located safely away from the pipelines and out of the flammable-liquid area. Accessories will introduce a hazard unless located so that the make-and-break contacts will function in a nonexplosive atmosphere.

(3) Thermal-electric conduction may be utilized by passing a low-voltage alternating current though the pipe. This method is commonly used to maintain a constant temperature in a system of piping when material in the storage tank has been previously warmed. Sufficient heat is supplied to the piping to compensate for normal heat loss in the system without raising the temperature of the liquid in transfer. Thermal-electric conduction systems is normally installed and tested as complete units by the manufacturer or his qualified agent. Sections of the piping to be heated are insulated by electrically nonconductive fittings from unheated sections to confine the current paths and to eliminate any current leakage at hazardous locations.

For thermal-electric conduction systems the following recommendations usually apply:

(a) An automatic high-temperature-limit safety cutoff switch is provided in each circuit of each system to prevent overheating of liquid in event of failure of the operating temperature-control thermostat.

(b) Each circuit is protected with fuses or fused disconnect switches of the lowest practical rating.

(c) All parts of the piping and fittings are enclosed in electrical- and thermal-insulating covering to prevent accidental grounding of the system.

(d) All switches, transformers, contactors, or other sparking units are located in a safe area away from any flammable liquid or vapor.

(e) The system is inspected and tested periodically to insure its continued safe operation. Maintenance of the installation is the responsibility of trained employees.

5.5.4 Valving and Controls

Valve functions can be defined as follows:

(1) On/off service
(2) Throttling service
(3) Prevention of reverse flow, or backflow
(4) Pressure control

(5) Special functions:
    (a) Directing flow
    (b) Sampling service
    (c) Limiting flows
    (d) Sealing vessel or tank outlets
    (e) Other.

Valve selection requires consideration of three basic and critical details:

(1) The flow control element
(2) The regulating mechanism
(3) The seal to contain the fluid within the valve.

In addition to these three important design aspects, features such as mechanical strength, materials of construction, dimensional arrangement, and types of end-connections are considered.

Valves are weak links in fluid transfer systems as regards leaks and fugitive emissions. There are three types of leakage:

(1) Process fluid escapes downstream, past flow-control element in closed position. Identified as "flow seal" leakage.

(2) Process fluid escapes to the outside of the valve, from around the stem and from the joints (bonnet) with the body. Identified as either stem-seal or bonnet-seal leakage.

(3) Air leaks into the valve body and to the process medium under vacuum.

Figure 5-30 shows a gate valve with the possible leakage areas around the stem packing, the bonnet assembly, and between the valve stem and packing gland.

5.5.5 Valving and Control Safety Consideration

5.5.5.1 Safety Shutoffs--

Hazardous and flammable-liquid pumping and piping systems are equipped with emergency shutoffs to stop the flow of liquid in event of fire or accidental escape of liquid or vapor. This can usually be done by safety shutoff valves and/or positive-displacement pumps. In general, these devices are arranged for automatic operation in event of fire and for manual or automatic operation in event of accidental escape of liquid. If the location of a possible fire can be accurately determined, as would be the case at dispensing locations, remote actuation is not necessary. If a fire could occur anywhere at an extensive installation, provision for remote actuation of the main safety shutoff valve will be needed.

(1) Safety shutoff valves are needed in flammable-liquid systems in the following locations:

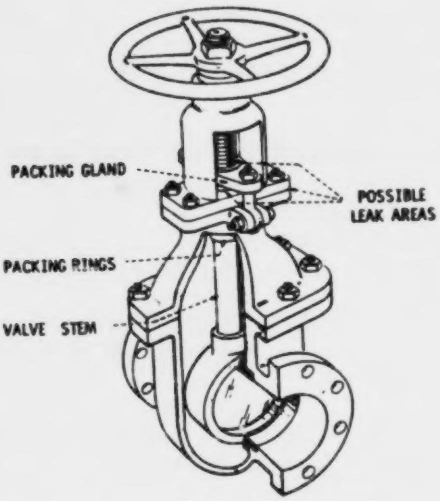


Figure 5-30. Three areas of a typical gate valve that can leak and result in fugitive emissions [2].

(a) At connections on supply and feed tanks where transfer is by gravity, centrifugal pump, inert-gas pressure, or other means that permits the maintenance of continuous pressure in the system. The possibility of siphon action through a centrifugal pump requires installation of a safety shutoff valve on the pump inlet.

(b) On feed lines where they enter important buildings or structures or on branch lines where they take off from main-supply headers. The valve is located out of doors or immediately adjacent to an exterior wall, accessible from outdoors.

(c) On feed lines at dispensing locations.

(2) Safety shutoff valves may be of the diaphragm, solenoid, or weight- or spring-operated fusible-element types. They generally incorporate some of the following design features:

(a) Have bodies with the appropriate service rating for the maximum pressure and temperature to be encountered. Bodies should be of cast steel, except that bronze is acceptable in sizes of 2 in. and less if under sprinkler protection.

(b) Close on failure of the operating electrical or air supply.

(c) Close in the direction of the liquid flow so that system pressure tends to hold the valve in the closed position.

(d) Close against a pressure of at least 150 per cent of design rating.

(e) Close within 5 seconds after actuation.

(f) Valve should not readily be bypassed, blocked, or otherwise made ineffective.

(g) Have an indicator to show when the valve is open or shut, except on packless solenoid types.

(h) Be manually reset, except where the valve-control circuit is arranged for manual resetting.

(i) Have no direct connections between the liquid and air section of diaphragm valves that might permit leakage of the liquid past the packing into the air lines.

(j) Have packing and lubrication, if any, resistant to the liquid being handled.

(3) Automatic operation of safety shutoff valves and/or direct-displacement pumps is normally accomplished by one of the following methods:

(a) Actuation by thermal devices located at the ceiling and above the point of flammable-liquid use where spills may be expected.

(b) Release of a dead-man control.

(c) Operation of the fire-protection system. With automatic sprinkler systems, actuation may be by waterflow indicators, alarm valves, or dry-pipe valves with hydraulic-pressure switches. With special fixed extinguishing systems, actuation is by pressure switches. Drain and alarm tests of sprinkler system are made during idle periods or arranged that they can be made without operating the safety shutoff.

(d) If the piping contains fragile components such as rotameters and sight glasses, the safety shutoff is actuated automatically by excessive pressure drop downstream from such components.

(4) Arrange safety shutoff valves and/or positive-displacement pumps for manual shutdown by use of one or more stop buttons or switches at safe and accessible locations throughout the flammable-liquid system. In general, such stop buttons or switches are located near points of egress from the building or structure.

(5) Self-closing manual valves and dead-man controls of a type not readily blocked open are recommended as emergency safety shutoffs on small systems, where liquid transfer is intermittent, and on larger

systems that lend themselves economically to such an arrangement. They require constant attendance by the operator and close automatically if he leaves.

(6) If normal flow in piping is in one direction only and the piping discharges to feed tanks, receivers, or other vessels so located that a leak in the piping upstream of these vessels could be fed by reverse flow through the piping, check valves are installed in the piping as close to the vessel as possible to prevent the reverse flow.

5.5.5.2 Gages, Meters, and Gage Glasses--

(1) Accessories on flammable-liquid piping systems, such as gages, meters, gage glasses, hydrometers, and sight glasses are designed to have strength equal to that of the piping system.

(2) Gage glasses are particularly susceptible to breakage. Their use is generally discouraged.

(3) Restricted orifices are used in piping to gages and instruments to reduce the amount of leakage in event of failure.

(4) Armored rotameters or instruments that read indirectly or sample a proportion of the flow in preference to those that enclose the entire stream or have the full flow directed to the glass reading chamber are also used. Vents on air releases used in conjunction with some metering devices are then piped to outdoors in order to dispose safely of flammable liquid that may be discharged if the float is inoperative.

5.5.5.3 Operating Controls--

(1) Operating control valves are located in hazardous and flammable-liquid piping systems so as to regulate the control and flow of liquids to connected equipment and to isolate equipment for maintenance purposes. Conventional types of valves are suitable for most liquids. Valves are used having the appropriate service rating for the maximum pressure and temperature to be encountered and packing or lubrication resistant to the liquid being handled. Valve bodies are normally of cast steel, except that bronze is acceptable on piping 2 in. or less in size in sprinklered locations. Cast-iron bodies are usually not used. If corrosive conditions or product purity require the use of special materials of construction, stainless-steel, Monel, or lined-steel valves are preferred to those made of more fragile materials.

(2) Valving is arranged to minimize the likelihood of improper operation. Rising-stem or other valves that indicate whether open or closed are preferred. The following recommendations for valve arrangements are generally followed where applicable:

(a) Three-way two-port valves are used at all branch lines so that flow can only proceed through one line.

(b) Plug-cock valves are used with a slotted guard arranged so that the handle can be removed only when the valve is in the closed position. This arrangement will prevent discharge through valves accidentally left open. One handle can serve all valves on the system.

(c) Electrical or mechanical interlocks are provided between valves so that the position of one valve with respect to another will be automatically determined.

(3) Where the correct sequence of additions of waste materials to a blending tank is of importance, sequence locks are used on valves in pipelines.

(4) Hydraulic accumulators or safety relief valves are provided on pipelines that can be valved off with liquid trapped between valves. This prevents damage or overpressure from thermal expansion. The discharge is piped from safety relief valves to a collection point.

(5) Tanks, mixers, and other equipment to which hazardous liquid waste is transferred are arranged so as to prevent accidental overflow. The best arrangement is a trapped overflow drain leading back to the source of supply or to a point of safe collection. The capacity of the overflow drain should be at least equal to that of the fill pipe.

(6) If the equipment normally operates under pressure so that an overflow drain is not practical but overflow is possible during filling because of open manholes or sampling connections, a liquid-level control is provided to stop the liquid flow by closing a valve or stopping the pump or to sound an alarm if the maximum safe level is approached or exceeded. Float valves or switches, pressure switches, and various other liquid-level indicators are available and may be used. Mechanical interlocking of valves on overflow drain and fill pipe can sometimes be arranged so that the overflow drain will be open when the fill-pipe valve is open.

(7) The use of accurate measuring devices, such as dispensing meters, measuring tanks, or weight tanks will assist greatly in the prevention of overflows. Dispensing meters permit a predetermined amount of liquid to pass and then automatically stop the delivery. Such meters control a spring-loaded quick-action valve that should be designed for manual starting with a hand-trip emergency shutoff.

(8) If control valves are to be remotely actuated, valves are chosen having characteristics described in recommendation 2 of Safety Shutoffs and arranged for operation in an emergency situation.

5.5.6 Solids Feeding Equipment

Waste material is pneumatically, mechanically, or gravity fed into an incinerator capable of burning solids. Normally, heterogeneous waste material must be reduced in size (shredded, pulverized, etc.) to facilitate the feed system operation and allow injection, distribution, and combustion within the incinerator.

In addition to reducing moisture content and waste material size, separation of noncombustible material such as ferrous and nonferrous metals may often be required. The former is removed using magnetic separators. Nonferrous metals are commonly removed using ballistic-type separators.

5.5.6.1 Shredders--

To reduce the size of waste materials for easier handling and feeding, shredders are used. Also, to expose all surfaces of hazardous waste containers (metal and fiber drums), it may be necessary to shred the containers. Usually, due to industrial hygiene, safety, and materials handling considerations, drums or packs of solidified residues cannot be shredded and must be charged directly into the incinerator [17]. Thus, it would be rare that a shredder would be used in conjunction with hazardous waste incineration, although in some applications, e.g., in-plant dedicated incinerators, shredders may be useful.

A shredder capable of consuming 55-gallon steel drums has to be a rugged unit, capable of containing dusts and mists of toxic materials as well as particles of steel thrown around at high velocity. This type of potential danger indicates a need for a hopper feed system to enclose flying debris, with mechanical feed from a conveyor so that plant personnel need never be in the vicinity of the hopper opening during operation. The hopper is elevated for gravity feed into the shredder, which also may be above ground level and well ventilated. A suction fan can then draw fumes and dust from the shredder into the incinerator or an alternate collection device.

A shredder capable of consuming 55-gallon drums would probably have a capacity for handling material several times as fast as the incinerator. Thus, some silo storage is necessary to safely contain the shredded material. The material discharged from the silo would go directly into the incinerator.

A shredding operation normally consists of a shredding unit and a transfer network including a variety of conveyors and feeders. Several types of shredding devices exist: vertical and horizontal axis hammer mills, vertical axis grinders, and horizontal axis impactors; horizontal hammer type shredders are the most common.

Unlike most other rotating equipment (pumps, fans, turbines, etc.), there is very little design criteria for predictable performance of mixed solid waste shredders. Size, style, and power selection is on an empirical basis, and this is not likely to change in view of the infinite types and combinations of input material.

There are three basic types of horizontal shaft swing hammer type shredders:

1. (1) Topfeed, single direction rotor rotation
2. (2) Topfeed, reversible rotor rotation
3. (3) Controlled feed, single direction rotor rotation.

Figure 5-31 illustrates a cross-sectional view of a horizontal axis shredder.

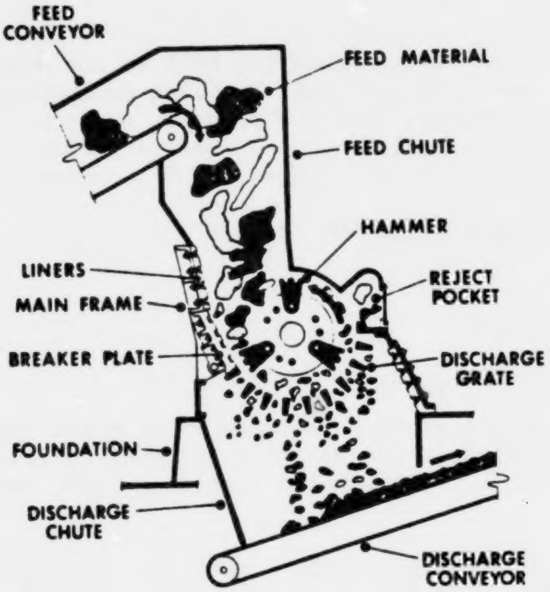


Figure 5-31. Cross-section through a nonreversible horizontal shredder [24].

5.5.6.2 Explosion Suppression and Safety Considerations for Shredders--
The primary explosion in a shredding system is a gas explosion caused by a friction spark and sometimes followed by a more violent dust explosion. Explosive dust mixtures of the type most likely to form in a solid waste shredder require a higher energy level for ignition than available from a friction spark. Explosion suppression systems have proved effective for gas and dust explosions on municipal solid waste shredders and are used on most installations. Today, most systems use a demand-inerting suppression system, whereby metal hemispherical containers release a suppressant in advance of a flame front. Such containers are connected to the shredding chamber by piping to channel the suppressant toward the interior of the chamber to provide blanket coverage. The most popular suppressant is Halon (short for halogenated hydrocarbon), a family of chemicals which possess unique properties with regard to fire extinguishing.

Also, sufficient pressure relief area is provided in the shredder and connecting superstructures such as hoods, ducts, or any connected enclosure. Excepting the shredder, this can be by means of hinged flaps, tethered blowout panels, and flexible flaps.

In addition, other means for minimizing personal injury and building damage are [25]:

1. Rigid enforcement of off-limits areas for roving personnel.
2. Complete enclosure protection for the shredder operator.
3. Separate or detached shredder building enclosures with blow-out sidewall and roof panels.
4. Partially open walls and/or roof.

5.5.6.3 Feeders--

Critical components in any system handling bulk solids are the feeders, which, in conjunction with conveyors and other handling equipment, transfer solids at a controlled rate from storage into the process, or from point-to-point within a process. Feeders may be called upon to transfer materials from railcar to storage bin, from storage bin to conveyor, or from conveyor to the incinerator.

There are four major types of solids feeders:

1. Rotary
2. Screw
3. Vibrating
4. Belt

Many specialized feeders are also available. Table 5-5 relates feeder types to material characteristics. The most common types of feeders which will be encountered in handling hazardous solid wastes are belt feeders and screw feeders.

Both belt feeders and screw feeders have their own limitations. Steps must be taken to alleviate dusting during operation of belt feeders. Total dust control can be assured only by enclosing the feeder with the proper dust entrainment hoods. Most manufacturers furnish enclosures for belts up to about 36 inches wide. These housings can be made gas-tight for inert-gas purging. However, if the user does not monitor feeder operation, or if a poor hopper design allows powder to avalanche onto the feeder belt, or if a dust collection system has not been provided to remove particles as they become airborne, the enclosure will serve only to contain the dust so that it eventually buries the feeder.

Caution is advised when using screw feeders with sticky or very cohesive materials. Such materials can build up in short pitch sections, and conveying will cease. For these services, longer-pitch, smoothly surfaced flights, multiple screws with overlapping flights, or ribbons instead of solid flights are normally specified.

Dust leakage around covers and along shaft seals is a common problem with screw feeders. "Dust tight" means little in a specification. Because this is an important requirement, "gas tight" to about one inch w.c. (water column) pressure is a term used. To ensure continued dust control, followup is normally needed during operation to make sure operators maintain seals, gaskets, and covers. Shaft seals are difficult to keep dust tight, especially if the

TABLE 5-5. FEEDERS FOR BULK MATERIALS

Material characteristics	Feeder type
Fine, free-flowing materials	Bar flight, belt, oscillating or vibrating, rotary vane, screw
Nonabrasive and granular materials, materials with some lumps	Apron, bar flight, belt, oscillating or vibrating, reciprocating, rotary plate, screw
Materials difficult to handle because of being hot, abrasive, lumpy, or stringy	Apron, bar flight, belt, oscillating or vibrating, reciprocating
Heavy, lumpy, or abrasive materials similar to pit-run stone and ore	Apron, oscillating or vibrating, reciprocating

trough is gas-purged. Even with the variety of seals offered, most will leak dust within a few hours unless shaft runout at the seal area is minimized. There is no standard industry specification covering runout; as much as 1/32 in. runout is not unusual. Manufacturers will furnish special construction for tight sealing, if this requirement is spelled out clearly in the specification.

Solid Waste Charging To Combustion Zone--The methods of feed to the combusion zone can be broken down as follows:

(1) Batch
  (a) open charging
  (b) air lock feeders
(2) Continuous

Batch open charging can be as simple as gravity feeding solid waste into a chute leading to the combustion zone, as in a rotary kiln incinerator.

An example of a batch air-lock feeder can be a charging hopper located above a rotary kiln inlet, charged by a grapple which is controlled from a fully air-conditioned operator cab, sealed against the bin space, using TV cameras and TV screen in a partially automatic, partially manual operation. The rotary kiln inlet is sealed from the bin space by a lock fitted with two sliding gates. When the inclined sliding gate in the drop chute of the rotary kiln inlet is closed, a horizontal sliding gate located in the charging hopper will open.

An example of a continuous solids feed is given in Figure 5-32, which illustrates a screw conveyor carrying sludge to a rotary feeder which is then pneumatically conveyed to a spin air nozzle within a fluidized bed incinerator.

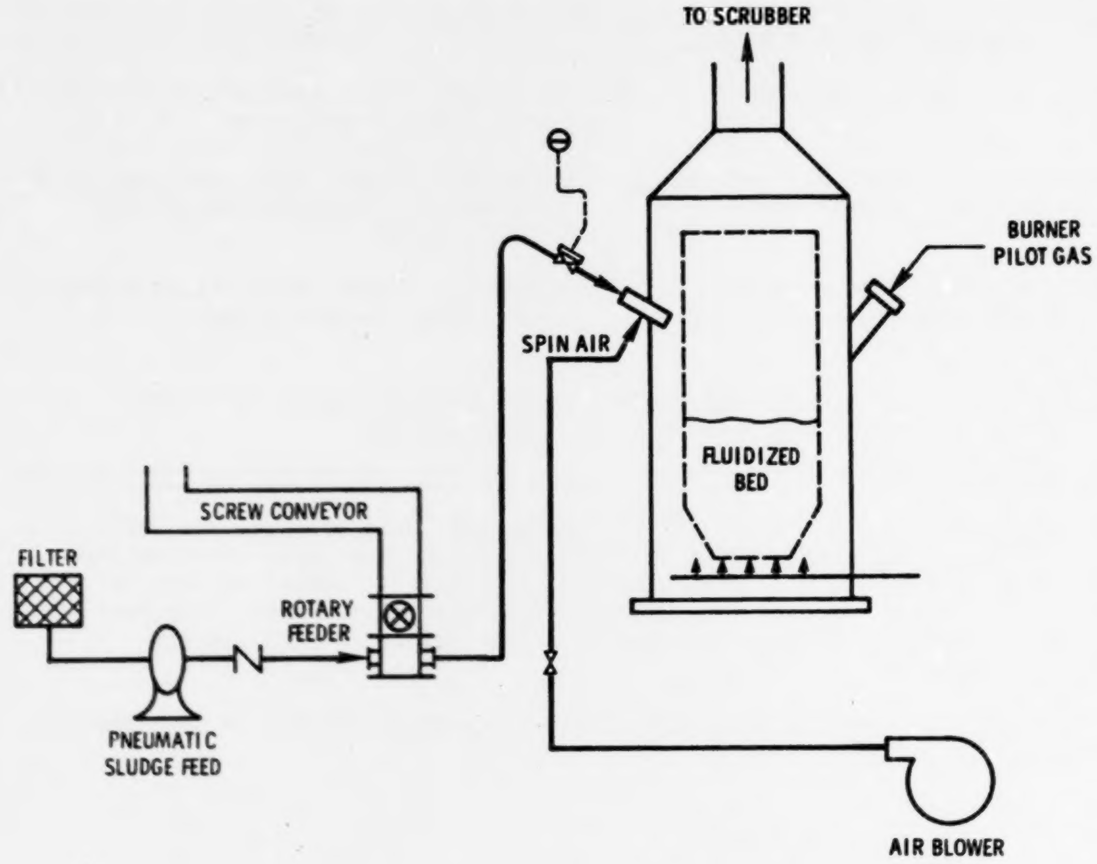

TO SCRUBBER
BURNER
PILOT GAS
SPIN AIR
FLUIDIZED
BED
SCREW CONVEYOR
FILTER
ROTARY
FEEDER
PNEUMATIC
SLUDGE FEED
AIR BLOWER

Figure 5-32. Continuous feeding of sludge to fluid bed incinerator.

5.5.6.4 Container Feeding Equipment--

For the most part, disposal technology for filled containers is appropriate for toxic materials and for materials which are not readily removable from the container. When opening the container might be harmful to operations personnel, the container should preferably be processed within a closed system. Furthermore, if the material cannot be easily poured, co-disposal of both the chemical and the container is preferable. Batch feeding of containerized solid wastes results in a cyclic waste loading that can contribute to reduced destruction and removal efficiencies [17].

In order to prevent the possibility of explosion or rapid temperature excursions, drummed material should not contain free-standing combustible liquids or even combustible liquids of high vapor pressure that are bound within solids or sludges. A series of holes are typically punched in the drums or other containers or their covers are removed to provide adequate venting. Small quantities of the material should be tested for thermal stability and exothermic decomposition at elevated temperatures before significant quantities are charged into the high-temperature environment of the rotary-kiln primary combustion chamber. It is often necessary to regulate the charge size of various containerized solids depending upon heat release characteristics [17].

There are three basic types of automated container feeding equipment to incinerators:

(1) Conveyor to air-lock charging to rotary kilns.
(2) Hydraulic drum and pack-feeding mechanisms.
(3) Conveyor to air-lock vestibule with puncturing apparatus to thermal treatment chamber.

Figure 5-33 illustrates a schematic diagram of a rotary kiln incineration system using air-lock charging of containers. A more detailed example of an air-lock waste charging system is given in Figure 5-34. The general practice of dropping small containers into a rotary kiln without emptying them has process disadvantages. Occasionally, there will be deflagrations with strong soot generation and excessive thermal and mechanical loading of the kiln refractories resulting from this practice. A separate explosion vent for the charging system is required to handle possible explosions.

A different type of container handling, feeding, and thermal treatment system is illustrated in Figure 5-35. The process includes a remote handling operation and a completely enclosed cannister punching operation. Containers are then thermally cleaned in the first thermal stage with the controlled volatilization of toxic chemicals.

The process described is excellent in the protection afforded to the operators by the remote automated handling, punching, and thermal disposal approaches. A wide range of containers or cannisters can be processed, including 55-gallon drums, chemical ton containers, munition cannisters, projectiles, and cans. Contaminated filter media have also been detoxified using the same technique.

The thermal furnace uses a containerized conveyor to transport the cannisters through the thermal process chamber, which is equipped with entry and exit vestibules with gas-tight doors at either end to facilitate the total containment of vapors which might escape from opened containers. Mechanized punching of the cannisters takes place within the entry vestibule.

5.5.7 Backup/Redundancy Provisions

The functional diagram of an incineration facility indicates that most components of the system are in a "series" configuration; each series component must be adequately functioning to avoid degraded performance. A few process components may be in a "parallel" configuration allowing a switchover to another component when problems are detected with an on-stream component. Examples are waste feed line filters which will usually have two or more units in parallel. Critical thermocouples for temperature measurement related to control functions and automatic shutoff must be redundant. Feed pumps are typically redundant; if plant processing rates are determined to be especially critical,

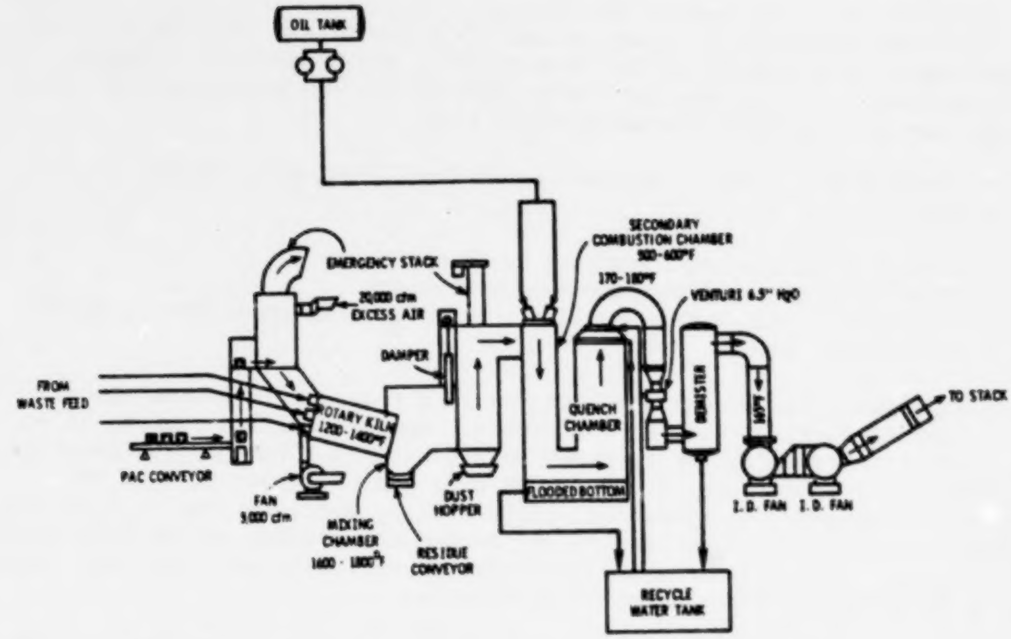

OIL TANK
SECONDARY
COMBUSTION CHAMBER
500-600°F
EMERGENCY STACK
170-180°F
VENTURI 6.5" H2O
20,000 cfm
EXCESS AIR
DAMPER
FROM
WASTE FEED
ROTARY KILN
1200-1400°F
QUENCH
CHAMBER
DEMISTER
TO STACK
PAC CONVEYOR
FAN
3,000 cfm
MIXING
CHAMBER
1600 - 1800°F
DUST
HOPPER
RESIDUE
CONVEYOR
FLOODED BOTTOM
I.D. FAN
I.D. FAN
RECYCLE
WATER TANK

Figure 5-33. Continuous type containerized toxic material thermal disposal process [26].

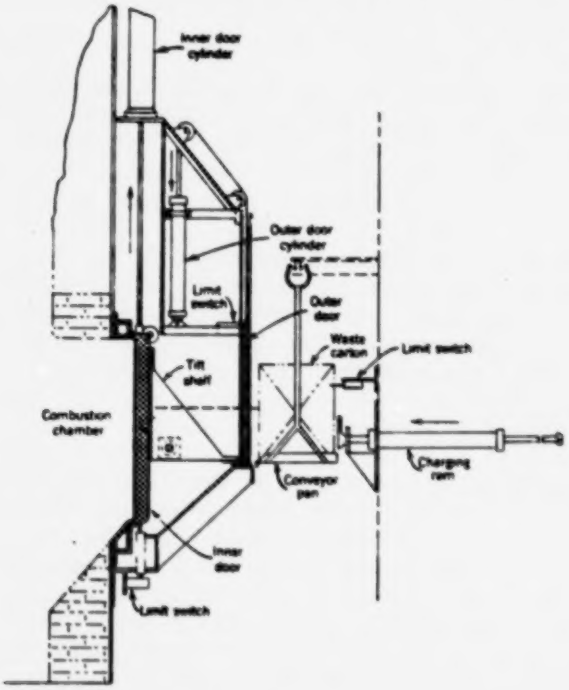

Inner door
cylinder
Outer door
cylinder
Limit
switch
Outer
door
Waste
carton
Limit switch
Tilt
shelf
Combustion
chamber
Charging
ram
Conveyor
pan
Inner
door
Limit switch

Figure 5-34. Example of a waste-charging door [27].

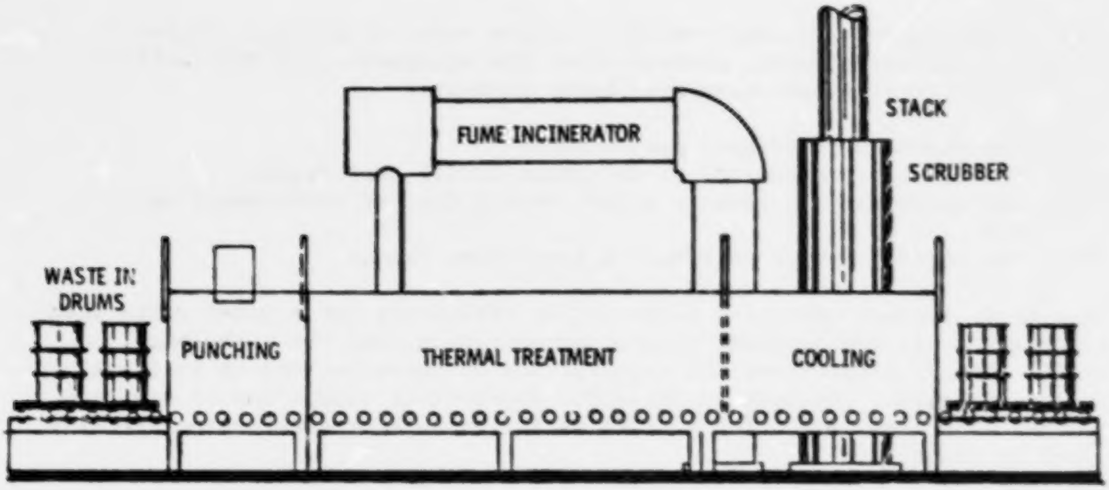


Figure 5-35. Liquid waste incinerator schematic [26].

redundant level monitors or extra gaging in critical storage tanks and silos, and flow monitoring cells may need backup devices to assure safety. A detailed failure mode analysis of each particular incinerator facility will identify the most likely potential malfunctions of each process element and point toward which safety systems cannot afford to fail for pointing out redundancy needs at a particular facility.

5.5.8 Waste Processing Instrumentation

An automated instrumentation system is used to transfer hazardous wastes from storage to the incinerator. Electrical and/or pneumatic systems permit observation of control, for all material handling, from a graphically illustrated control panel which shows such things as discharge valve positions, pump motor operation, storage tank and bin levels (high and low), storage tank agitator operation, and liquid or solid waste flow. The control instrument technology has been well developed. Instrumentation used in oil-burning utility systems is excellent. The difficulty encountered in the hazardous waste liquid application is caused by the nature of the product. It is invariably corrosive, contains particulate, and has a nasty tendency to foul the surfaces it contacts. The flow-sensing system is the heart of the control problem [15]. Equipment operation including belt conveyors, shredder, bucket elevator, or screw conveyors to the incinerator can also be displayed.

5.6 COMBUSTION PROCESS MONITORING

Before incineration process conditions can be controlled automatically they must be measured with precision and reliability. Instrumentation for an incineration process is essential because of the variability of the many factors involved in attaining good combustion. For example, as the heat content of the solid waste rises, changes in the combustion process become necessary. Instrumentation indicates these variations so that automatic or manual control adjustments can be made.

The uses of instrumentation and controls include means of process control, protection of the environment, protection of the equipment, and data collection. A control system must have four basic elements:

(1) the standard of desired performance;
(2) the sensor (instrument) to determine actual performance;
(3) the capability to compare actual versus desired performance (error), and
(4) the control device to effect a corrective change.

The four major factors governing incineration efficiency for a given waste feed are temperature, residence time, oxygen concentration, and the turbulence achieved. Chapter 4 discusses the significance of these factors in incinerator design and operation. Methods to determine appropriate conditions of temperature, residence time, etc., for a given waste/incinerator combination are also described in Chapter 4.

To comply with RCRA and EPA regulations, monitoring is required for combustion temperature, waste feed rate, air feed rate, carbon monoxide, carbon dioxide, excess oxygen, particulate matter, hydrogen chloride, and nitrogen oxides.

Temperature in the incinerator can be directly measured. Instrumentation is also available to directly monitor CO, CO_2, and oxygen concentration in the combustion gas to insure that excess air levels are maintained. Residence time and mixing efficiency cannot be directly measured, however, so other parameters indicative of these conditions need to be measured instead.

Gas residence time in the combustion zone depends upon the volume of the combustion chamber and the volume flow rate. Since the volume of the chamber is fixed for a given unit, residence time is directly related to combustion gas volume flow rate. Therefore, measuring this flow rate is equivalent to residence time measurement for a given incinerator.

Mixing in liquid waste incinerators or afterburners is a function of burner configuration, gas flow patterns, and turbulence. Burner configuration and gas flow pattern are a function of the incinerator design and will not vary from baseline conditions. Turbulence is determined by gas velocity in the combustion chamber, which is proportional to gas volume flow rate. Therefore, combustion gas flow rate is an indicator of mixing as well as residence time in liquid injection incinerators.

In incinerators burning solid hazardous wastes, other factors need to be considered to determine solids retention time and degree of agitation. These factors, which vary from one type of incinerator to another, are discussed in Section 5.6.4. Sections 5.6.1 through 5.6.3 discuss where and how temperature, oxygen concentration, and gas flow rate can be measured.

5.6.1 Temperature Monitoring

Incinerator temperature is monitored on a continuous basis to assure that the minimum acceptable temperature for waste destruction is maintained.

This requires one or more temperature sensors in the hot zone and a strip chart recorder or equivalent recording device.

Generally, wall temperatures and/or gas stream temperatures are determined using shielded thermocouples as sensors. Thermocouples are the most commonly used contact sensors for measuring temperatures above 1,000°F. Specifically, thermocouples can measure the following thermal parameters:

a. Average gas temperature - accomplished using a shielded thermocouple with relatively large thermal capacity anchored to a relatively large mass. The metering circuit is provided with a 30-second time constant to further smooth and average the readings.

b. Instantaneous gas temperature - accomplished using a shielded thermocouple with very small thermal capacity with the output metered by a circuit with a 1-second time constant. (Nominally, the reaction rates within the hot gas stream should be strongly temperature dependent; they thus should depend on the highest temperature to which the constituents are exposed.)

c. Open flame temperature - obtained using an unshielded low thermal mass thermocouple with the output metered by an amplifier with a 30-second time constant.

d. Average wall temperature - obtained using a shielded thermocouple imbedded in the refractory wall. (Here, the averaging is accomplished by the thermal inertia of the refractory material.)

Optical pyrometers are not recommended for these measurements due to spectral bias factors present in the combustion area which can cause unacceptable measurement error.

The location at which temperature measurements are taken is important, due to possible variations from one point to another in the combustion chamber. Temperatures are highest in the flame and lowest in the refractory wall or at a point of significant air infiltration. Ideally, temperatures are measured in the bulk gas flow at a point after which the gas has traversed the combustion chamber volume that provides the specified residence time for the unit. Generally, temperature measurement at a point of flame impingement or at a point directly in sight of radiation from the flame is not recommended. Figures 5-36 and 5-37 show typical monitoring locations for liquid injection and rotary kiln incinerators, respectively.

The types of thermocouples used include J, K, E, R, S, and B. The letter symbols identifying the thermocouple types are those defined in ANSI Standard C96.1. These symbols are in common use throughout industry:

Type J - Iron versus constantan (modified 1913 calibration)

Type K - Originally Chromel-P versus Alumel

Type R - Platinum 13% rhodium versus platinum

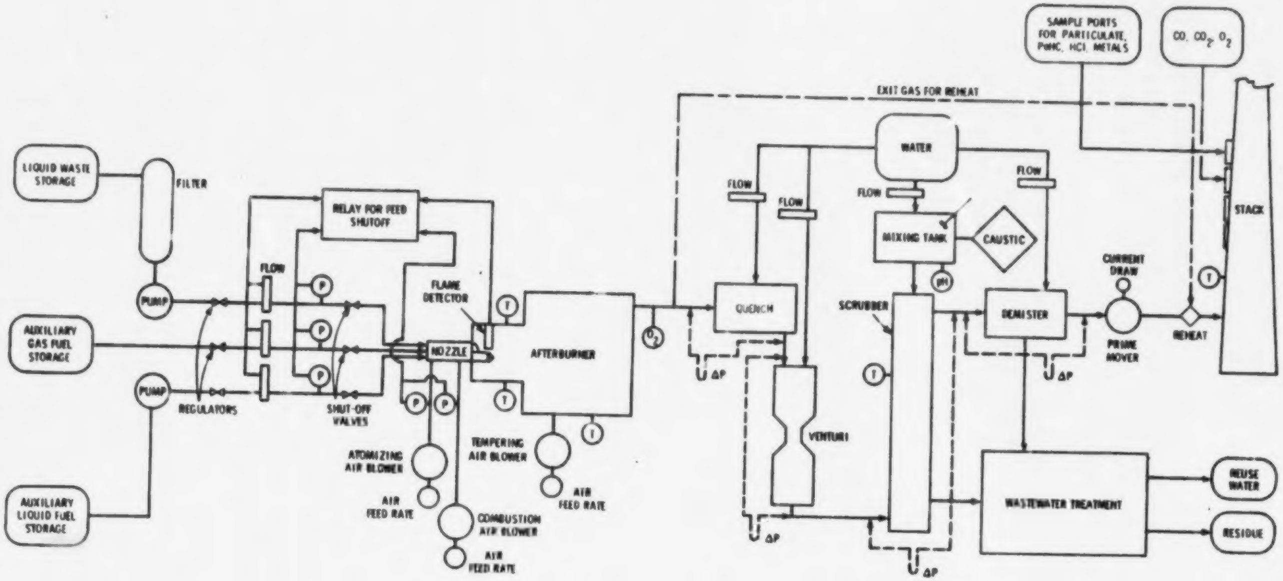

LIQUID WASTE STORAGE
FILTER
PUMP
AUXILIARY GAS FUEL STORAGE
PUMP
AUXILIARY LIQUID FUEL STORAGE
REGULATORS
FLOW
P
P
P
SHUT-OFF VALVES
RELAY FOR FEED SHUTOFF
FLAME DETECTOR
NOZZLE
P
P
ATOMIZING AIR BLOWER
AIR FEED RATE
COMBUSTION AIR BLOWER
AIR FEED RATE
T
T
AFTERBURNER
TEMPERING AIR BLOWER
AIR FEED RATE
T
O2
EXIT GAS FOR REHEAT
FLOW
QUENCH
ΔP
FLOW
VENTURI
ΔP
WATER
FLOW
MIXING TANK
CAUSTIC
pH
SCRUBBER
T
ΔP
FLOW
DEMISTER
ΔP
WASTEWATER TREATMENT
REUSE WATER
RESIDUE
CURRENT DRAW
PRIME MOVER
REHEAT
T
STACK
SAMPLE PORTS FOR PARTICULATE, PoHC, HCl, METALS
CO, CO2, O2

Figure 5-36. Schematic diagram showing typical monitoring locations for a liquid injection incinerator.

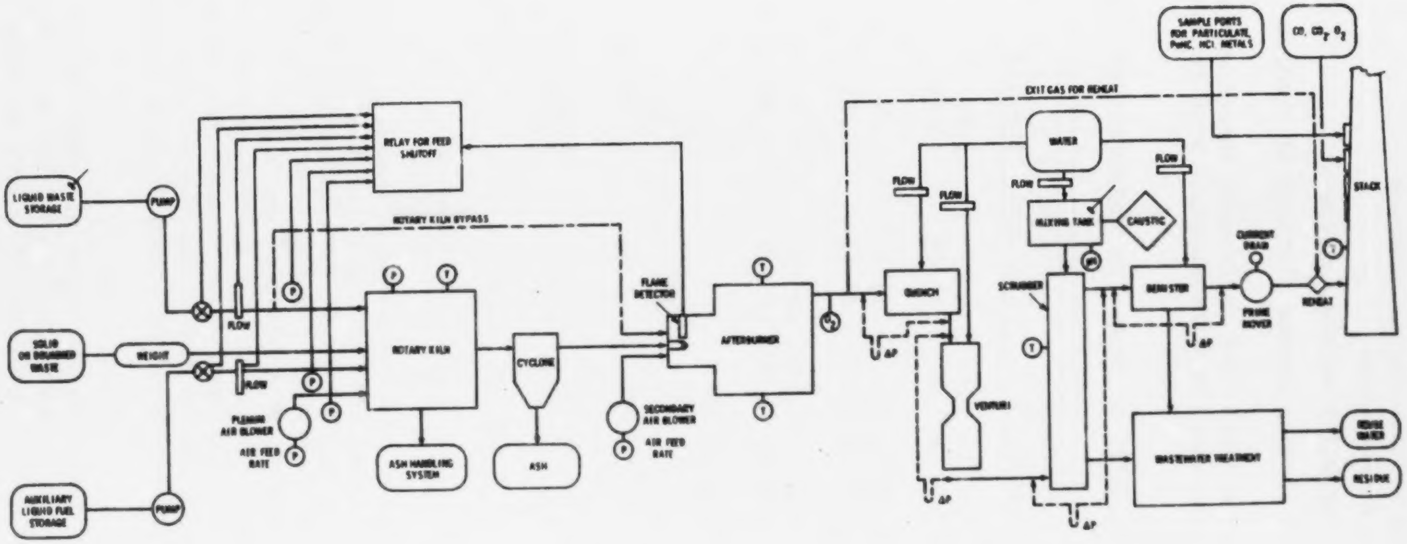

LIQUID WASTE STORAGE
SOLID OR DRUMMED WASTE
AUXILIARY LIQUID FUEL STORAGE
PUMP
WEIGHT
PUMP
FLOW
FLOW
RELAY FOR FEED SHUTOFF
ROTARY KILN BYPASS
P
P
P
P
T
ROTARY KILN
PLENUM AIR BLOWER
AIR FEED RATE
P
ASH HANDLING SYSTEM
CYCLONE
ASH
FLAME DETECTOR
SECONDARY AIR BLOWER
AIR FEED RATE
P
T
AFTERBURNER
T
O_2
EXIT GAS FOR REHEAT
QUENCH
FLOW
FLOW
ΔP
VENTURI
ΔP
WATER
FLOW
MIXING TANK
CAUSTIC
pH
SCRUBBER
T
ΔP
FLOW
DEMISTER
ΔP
CURRENT DRAW
PRIME MOVER
REHEAT
T
STACK
SAMPLE PORTS FOR PARTICULATE, POHC, HCl METALS
CO, CO_2, O_2
WASTEWATER TREATMENT
REUSE WATER
RESIDUE

Figure 5-37. Schematic diagram showing typical monitoring locations for a rotary kiln incinerator.

Type S - Platinum 10% rhodium versus platinum
Type T - Copper versus constantan

Type E - Originally Chromel-P versus constantan

Type B - Platinum 30% rhodium versus platinum 6% rhodium

Table 5-6 lists the limits of error for the common thermocouple types; most manufacturers supply thermocouples and thermocouple wire to these limits of error or better.

TABLE 5-6. LIMITS OF ERROR FOR THERMOCOUPLES [28]

Type	Temperature range, °F	Limits of error Standard	Limits of error Special
J	32 to 530	±4°F	±2°F
	530 to 1,400	±3/4%	±3/8%
K	32 to 530	±4°F	±2°F
	520 to 2,300	±3/4%	±3/8%
R, S	32 to 1,000	±5°F	±2-1/2°F
	1,000 to 2,700	±1/2%	±1/4%
T	-300 to -75		±1%
	-150 to -75	±2%	±1%
	-75 to +200	±1-1/2°F	±3/4°F
	200 to 700	±3/4%	±3/8%
E	32 to 600	±3°F	±2-1/4°F
	600 to 1,600	±1/2%	±3/8%
B	1,600 to 3,100	±1/2%	

Since the thermocouple element in a thermocouple assembly is usually expendable, conformance to established emf-temperature relationships is necessary to permit interchangeability. Calibration of a thermocouple consists of the determination of its emf at a sufficient number of known temperatures such that with some accepted means of interpolation its emf will be known over the entire range in which it is to be used. The process requires a standard thermometer with a high-level calibration to indicate temperatures on a standard scale, a means for measuring the emf of the thermocouple, and a controlled environment in which the thermocouple and standard can be brought to the same temperature [28].

Thermocouples use one of three different types of measuring junctions--grounded, ungrounded, and exposed. The grounded junction is the most popular. The ungrounded junction is the most rugged, but its speed of response is slower than that of the grounded type. The unprotected exposed junction responds the fastest but is more vulnerable to corrosion and mechanical damage.

A complete thermocouple assembly consists of the following:

1. A sensing element assembly, including in its most basic form two dissimilar wires joined at one end and separated by an electrical insulator
2. A protection tube, either ceramic or metal, or a thermowell. In some cases, both primary and secondary protection tubes are used
3. A thermocouple head or connector
4. Miscellaneous type hardware such as pipe nipples or adaptors to join the protection tube to the head and thermocouple glands for mounting and pressure sealing

Protection tubes and thermowells serve the double purpose of guarding the thermocouple against mechanical damage and shielding it from corrosive atmospheres. The choice of the proper material for the protection tube or thermowell is governed by the conditions of use and by the tolerable life of the thermocouple. There may be times when the strength of the protection tube is more important that the long term stability of the thermocouple. On the other hand, gas tightness, resistance to thermal shock, or chemical compatibility of the protection tube with the process may be the deciding factors [28].

The most common forms of protection tubes and thermowells and their applications are covered in the following subsections [28].

5.6.1.1 Metal Tubes--

Metal tubes offer adequate mechanical protection for base metal thermocouples at temperatures to 1,423 K (1,100°F; 1,150°C). It must be remembered that all metallic tubes are somewhat porous at temperatures exceeding 1,088 K (1,500°F; 815°C) so that, in some cases, it may be necessary to provide an inner tube of ceramic material [28].

(a) Carbon steels can be used to 973 K (1,300°F; 700°C) usually in oxidizing atmospheres.

(b) Austenitic stainless steels (300 series) can be used to 1,143 K (1,600°F; 870°C), mostly oxidizing although Types 316, 317, and 318 can be used in some reducing atmospheres.

(c) Ferritic stainless steels (400 series) can be used from 1,248 K to 1,423 K (1,800°F to 2,100°F; 975°C to 1,150°C) in both oxidizing and reducing atmospheres.

(d) High nickel alloys, Nichrome, Inconel, etc., can be used to 2,100°F (1,150°C) in oxidizing atmospheres [28].

Where the protection tube is subject to high pressure or flow-induced stresses or both, a drilled thermowell often is recommended. Although less expensive metal tubes, fabricated by plugging the end of the protection tube, may satisfy application requirements, more stringent specifications usually dictate the choice of gun-drilled bar stock, polished and hydrostatically tested as a precaution against failures [28].

5.6.1.2 Ceramic Tubes--

Ceramic tubes are usually at temperatures beyond the ranges of metal tubes although they are sometimes used at lower temperatures in atmospheres harmful to metal tubes [28].

The ceramic tube most widely used has a Mullite base with certain additives to give the best combination of mechanical and thermal shock properties [upper temperature limit 1,923 K (3,000°F; 1,650°C)] [28].

Silicon carbide tubes are used as secondary protection tubes. This material resists the cutting action of flames. It is not impermeable to gases and, where a dense tube is required, a nitride-bonded type material can be obtained so that the permeability is greatly reduced [28].

Fused alumina tubes can be used as primary or secondary protection tubes or both where temperatures to 2,253 K (3,600°F; 1,980°C) are expected and when a gas-tight tube is essential. Fused alumina tubes and insulators should be used with platinum-rhodium, platinum thermocouples above 2,200°F (1,200°C) in order to ensure long life and attain maximum accuracy. [The Mullite types contain impurities which can contaminate platinum above 2,200°F (1,220°C). The alumina tubes are more expensive than the Mullite base tubes, but types impervious to most gases to 2,088 K (3,300°F; 1,815°C) can be obtained] [28].

5.6.1.3 Metal-Ceramic Tubes--

"Cermets" are combinations of metals and metallic oxides which, after proper treatment, form dense, high-strength, corrosion-resistant tubes usable to about 1,698 K (2,600°F; 1,425°C) in most atmospheres [28].

5.6.2 Oxygen Monitoring

Oxygen concentration in the combustion gas is usually measured at a point of high turbulence, after the gas has traversed the full length of the combustion chamber. A good location for measurement is at the inlet to the duct leading from the combustion chamber to the quench zone, immediately after the gas has gone through a 90° turn. Figures 5-36 and 5-37 show this location.

Oxygen measurements are made on a continuous basis. Commercially available instruments are discussed in Section 5.9. Whichever type of sensor is used, it is typically equipped with a gas conditioning system specified by the manufacturer for the gas environment in which the instrument is used.

When measuring oxygen concentration directly in the high-temperature flow, some difficulty can be experienced because of molten slag impingement on the probe. Trial-and-error solutions of location and probe length have minimized this problem. A redundant system for scheduled maintenance is desirable [15].

5.6.3 Gas Flow Measurement

Gas flow rates can be measured or approximated in several ways: by insertion in the flue gas duct of an air pressure measuring element (e.g., pitot tube) or by measuring the drop in pressure across a restriction to the gas flow (e.g., baffle plate, venturi section, or orifice) downstream of the combustor. Exhaust gas flow, however, is the most difficult flow measurement application on the incinerator for many reasons:

(1) Because the gas is dusty, moist, and corrosive, pressure taps will tend to plug. For this reason it is extremely important that the connection to the duct be made sufficiently large and with cleanout provision.

(2) If the two pressure sensing points are at widely different temperatures, the resulting difference in density of the gas in the connecting lines to the instrument will create an error in measurement. For this reason, avoid measurement across spray chambers or other locations where gas temperature changes radically [29].

(3) If taken across a restriction to gas flow, the fouling tendencies of the dirty gas will cause the restriction to increase with time, thereby changing the differential measurement for a given rate of flow [29].

For the reasons stated above, the usefulness of this measurement as an indication of quantitative flow is limited and care should be taken in this application [29].

Flow measurements are performed at either of two locations: (1) in the duct between the combustion chamber and quench zone, or (2) in the stack (Figures 5-36 and 5-37). Both locations have their advantages and disadvantages. In the combustion chamber outlet duct, a sufficiently long length of duct may not be available for flow pattern development. Access to this location can also be a problem when the incinerator is vertically oriented and because of the necessity to breech the duct at a high temperature point. High temperatures at this location may require special materials of construction (e.g., inconel) for measurement elements.

The advantages of flow rate measurement in the stack are relief of the problems associated with high temperature gas flow measurement, increased accessibility to the gas flow, and increased likelihood of having a proper section of duct for the flow measurement. One minor disadvantage associated with this position is the increased possibility that ambient air leaks into the system upstream of the draft fan could bias the flow measurement. This is not a common occurrence, however, and good facility management practice will normally detect such leaks quickly.

Of the instruments available to measure gas flow in closed conduits, pressure or velocity head meters are among the oldest and most common. The principal shortcomings are the need for elements to be inserted directly into the flow paths (in contact with th gas stream), making them susceptible to corrosion, erosion, and fouling; the requirement for seals; the likelihood that the conduit may have to be opened for inspection or service; and permanent pressure losses caused by restrictions placed in the channels.

Head-type flowmeters incorporate primary elements, which interact directly with the streams to induce velocity changes, and secondary elements, which sense the resulting pressure perturbations. The flow rate of interest is a function of the differential pressures which can be detected.

5.6.3.1 Orifice Plates--

Orifice plates, the predominant primary flow elements, can yield accuracy and repeatability of ±0.25 to 2% full scale at Reynolds numbers from 8,000 to 500,000 [29]. Units are offered in a variety of designs, with flow area shapes which can be:

(1) Concentric
(2) Eccentric
(3) Segmental,

and profile cross sections which can be:

(a) Square-edged
(b) Sharp-edged
(c) Quadrant-edged
(d) Double bevel
(e) Conical inlet.

Principal advantages include low cost, interchangeability, and installation with minimal modification of piping systems. The greatest disadvantages are high unrecoverable pressure loss, requirement for skill in installation and making pressure connections, need for long runs of unobstructed piping or use of straightening vanes upstream and downstream of the primary element to achieve accuracy, and sensitivity of measurement reliability to orifice geometry and surface conditions which can vary as a result of normal use or handling [29].

Orifice plates can be specified in corrosion-resistant materials appropriate for many operating conditions. For fluids above 600°F, plate materials should be specified that have thermal expansion coefficients matched with those of the mounting flanges, and effort should be made to moderate the rate of temperature change on the complete primary assembly to avoid thermal stresses [29].

The most common orifices have sharp, square, or rounded upstream edges. Circular concentric designs are particularly popular since accuracy is highly predictable and extensive performance data are available for broad ranges of flow rates, duct sizes, pressure differentials, and other application factors. Eccentric and segmental orifice designs may be considered when the measured fluid contains suspended materials since these may lead to accumulations behind concentric plates and cause erratic or false readings [29].

5.6.3.2 Venturi Tubes--

Venturi tube configurations can be standard, eccentric, or rectangular. In standard designs, cylindrical barrel sections having inner diameters close to those of the main pipes connect to the throat sections through cones of fixed angular convergence; the throats terminate in diverging exit cones which again match the inner pipe diameters. Eccentric venturi elements are available to handle flows with mixed phases, and rectangular units can be specified for use in noncircular ducts [29].

Venturis handle 25% to 50% more flow than orifices for comparable line size and head loss. The flow range for satisfactory measurement is usually considered to extend upward from Reynolds numbers of about 200,000. Advantages, in addition to capacity, include high pressure recovery, good accuracy with beta ratios greater than 0.75, integral pressure connections, minimal requirements for straight runs of upstream piping, and suitability for dirty applications because the streamlined inner surfaces resist erosion and particle accumulation. Purchase cost is high compared with most other primary elements, but the greater pressure recovery can result in significant energy savings in large ducts. A more significant problem is that large sizes make the tubes awkward to install [29].

5.6.3.3 Pitot Tubes--

Pitot tubes are the simplest velocity head sensors. Models can be specified for a variety of difficult fluid services, including high temperature, high pressure, and corrosive, dirty gases. Moreover, the sensors are formed as probes, which often are designed to be inserted in conduits without system shutdown [29].

Numerous special as well as standard configurations are available; for instance, models can be ordered to measure velocity direction as well as magnitude. Limitations include tendency to plug when fluids contain suspended solid particles unless provision is made for purging or flushing, narrow velocity ranges with standard secondary elements, and sensitivity to local distrubances in the flow pattern [29].

Another fundamental problem is that measurement indicates velocity at one point in the stream, rather than providing integrated volumetric flows. The probes must be traversed across the pipes or the velocity profiles known in advance to calculate average flow. Moreover, to avoid uncertainty about local perturbations, at least 8 diameters of straight smooth pipe are recommended upstream of typical devices [29].

5.6.4 Solid Waste Retention Time and Mixing Characteristics Information

Retention time for nonvolatile or solid wastes in an incinerator is different from that for volatiles. When solid wastes are being incinerated using incinerators which have mechanical means for agitating and moving solids through the combustion zone such as is possible with rotary kilns and multiple hearth incinerators, residence time of nonvolatiles will become a function of these variables. Mixing will also become a variable when rabble arms or other mechanical devices are used to tumble or otherwise break up chunks of solid material. Residue analysis is typically performed to ascertain the condition of the ash produced at these conditions. If analysis shows that insufficient agitation or residence time is being achieved in exposing the solids to combustion zone conditions, a change of those conditions is normally requested to eliminate the problem.

5.7 AIR POLLUTION CONTROL DEVICE INSPECTION AND MONITORING

5.7.1 Wet Scrubbers

Five parameters are routinely checked on wet scrubbers to monitor their operational effectiveness. These are discussed below. Gas and liquid flow rates are discussed together in Section 5.7.1.2

5.7.1.1 Temperature--

Deviations from the design temperature can have serious effects on the removal efficiency of a wet scrubber, particularly when the scrubber is being used to remove gaseous components. Since incineration inherently produces high temperature gas to be scrubbed, pre-cooling of the gas stream is necessary. Units used for this are commonly called quench towers, and they normally bring the gas temperature down to around 150°F prior to entry into the scrubber. This scrubber inlet temperature is continuously monitored to assure that proper scrubbing conditions are maintained in accordance with the design inlet temperature value or range. Deviations can cause several effects, including rapid loss of scrubbing liquid, compromise of absorption efficiency, undue corrosion, and structural damage to the unit. One or more of these occurrences can increase emissions from the unit. Figures 5-36 and 5-37 show the approximate position for temperature measurement. Emergency shut down features regarding this temperature measurement are discussed in Chapter 4.

5.7.1.2 Liquid and Gas Flows--

A wet scrubber must provide good gas-liquid turbulence and optimum contacting surfaces for proper absorption of contaminant gases or removal of particles [30]. This provision is typically specified by the vendor and normally expressed as the liquid-to-gas ratio (e.g., 5 gpm/1,000 cfm [L/G]). A certain L/G will be necessary to achieve design removal efficiency. The vendor also supplies the sensitivity of the L/G ratio to removal efficiency because each design has a somewhat different sensitivity to the L/G ratio. With this data in hand, a range of acceptable L/G ratios can be established, consistent with removal efficiency requirements. This range serves as the parametric limits for acceptable L/G ratio operation. System gas flow will have been measured as part of the incinerator operating requirement covered previously. Therefore, scrubber liquid flow rate measurement will provide the remaining necessary parameter measurement to define the L/G ratio. This parameter is monitored often and remedial actions taken by the operator, should the ratio exceed the parametric limits. Operator action will normally be a minor adjustment of the scrubber liquid flow rate.

A measurement of the moisture content of the gas leaving the scrubber is made in cases where some other device is in the system which can contribute additional moisture to the total gas flow such as a mist eliminator. This also covers the situation where the gas flow measurement may be made upstream of the quench zone in the hot gas area. In the case of the hot zone measurement, the sum of hot zone gas flow plus moisture content corrected to scrubber pressure and temperature conditions represent scrubber gas flow. Obviously, a direct measurement of the gas flow exiting the scrubber may also be used, but this will necessitate another measurement system set-up.

Measurement of the liquid flow rate is accomplished by using any of several types of flowmeters, including venturi, orifice, flow tube, pitot tube, magnetic, or acoustic varieties. Device acceptability considerations are summarized in Table 5-7. Figures 5-36 and 5-37 show the appropriate measurement location.

5.7.1.3 pH--

Another important parameter in wet scrubber operation is pH. Materials of construction are selected in part based upon the degree of acidity or alkalinity provided by the scrubbing liquid during operation. Deviation from the design pH condition or range may result in deterioration of the scrubber structure in contact with the liquid. Furthermore, maintenance of the pH design condition is important to scrubber liquid absorption efficiency when removing gaseous contaminants.

The liquid composition and its attendant pH will be determined during the design phase. Absorption efficiency can change drastically as a function of pH, thereby altering the scrubber removal efficiency, so an acceptable pH variation range is designed for the equipment. The pH is monitored continuously and either manual (operator) or automatic adjustment made to keep the pH within proper operating specifications. A number of commercially available pH monitoring systems can adequately serve this purpose. These systems normally include a direct readout device which can be conveniently located on a control panel for continuous monitoring accessibility. Figure 5-42, Section 5.8, shows the measurement location and arrangement for scrubber liquid pH.

5.7.1.4 Pressure Drop--

Pressure drop is an important indicator parameter in monitoring the operational condition of a wet scrubber. It is sensitive to changes in the gas flow rate, liquid flow rate, and clogging phenomena in the system. During the design phase, a proper pressure drop value or range to maintain design removal efficiency is specified. Monitoring this parameter provides a continuous, additional check on the normal operation of the scrubber. A change in the pressure drop is an indication that other measured parameters in the system need to be observed immediately to find the cause of the disturbance and corrective action should be taken. It is also an indicator which covers the time span between other routine parameter checks. If, after checking the pH, temperature, and gas and liquid flow rates, all appears in order, then the pressure drop measuring system is checked for correct operation and a visual inspection of the scrubber conducted to identify possible clogging problems. A check of the control efficiency is also routinely made to see if removal efficiency is being maintained.

Many kinds of pressure measurement devices are commercially available to measure pressure drop across a device; however, a differential pressure gage calibrated in inches of water is usually recommended for this purpose. The readout device is located in a convenient place for the operator to observe at any time. Figures 5-36 and 5-37 show the location of the pressure taps relative to the device.

TABLE 5-7. DEVICES FOR LIQUID FLOW MEASUREMENT

Flow measurement device	Advantages	Disadvantages	Flow range, gpm (applicable pipe diameter)
Venturi meter	Low permanent pressure drop. Applicable to streams with appreciable solids content. Accurate.	Flow disrupted and plumbing modifications required for installation. Expensive.	0-750 (1-18 in.)
Orifice meter	Inexpensive.	Flow disrupted and plumbing modifications required for installation. Large permanent pressure drop. Solids may deposit behind device. Moderately accurate.	0-750 (0.5-30 in.)
Flow tube	Applicable to streams with appreciable solids content.	Flow disrupted and plumbing modifications required for installation. Intermediate permanent pressure drop. Moderately expensive. Moderately accurate.	0-750 (1-18 in.)
Pitot tube	Low permanent pressure drop. Inexpensive method for pipes of large diameter.	Flow disrupted and plumbing modifications required for installation. Solids may cause plugging. High flow velocities may cause instability. Moderately accurate.	250-50,000
Magnetic meter	Minimum permanent pressure drop. Applicable to streams with appreciable solids content. Accurate.	Flow disrupted and plumbing modifications required for installation. Expensive. Electrodes may be fouled by wastewaters containing oil and grease. Susceptible to electromagnetic interference from nearby equipment.	250-20,000 (0.1-100 in.)
Acoustic meter	Installation without flow disruption. Relatively accurate. No head loss or pressure drop. Applicable to streams with appreciable solids content. Portable.	Expensive. Moderately accurate.	250-20,000 (pipes of all diameters)

In selecting a pressure measuring device, the following items are considered:

- Pressure range
- Temperature sensitivity
- Corrosivity of the fluid
- Durability
- Frequency response

A guide to pressure sensing device selection is summarized in Table 5-8.

5.7.1.5 Residue Generation--

Generation of residue from wet scrubbers results from operational requirements of the scrubber liquid in the specific system used. Vaporization losses in the contacting area create the need for make-up liquid to be provided, and changes in liquid pH create the need for adjustment. Collected material (such as solid particles) also creates abrasion, contamination, and corrosion problems in the scrubbing liquid and/or transport system. In addition, when hazardous materials are collected, a need for further treatment may be created prior to disposal. Sometimes a designer will choose to accommodate these problems in an integrated system design approach. Monitoring requirements relative to generation of residue from a wet scrubber are those required for observation of waste stream treatment systems and are covered in Section 5.8. Control of pH is also discussed.

5.7.2 Fabric Filters

Fabric filters basically consist of a porous layer of flexible, textile material through which a contaminated gas is passed to separate entrained material from the gas stream [32]. As collected material accumulates, resistance to the gas flow increases. The collected material is removed periodically by vigorously cleaning the filter to maintain proper pressure drop across the system.

Certain fabric filter parameters are monitored on a regular basis to evaluate operational effectiveness. These are detailed below.

5.7.2.1 Temperature--

A limiting factor in filtering hot gases with a fabric filter is the temperature resistance of the fibrous materials from which the filter cloth is made. Therefore, the manufacturers temperature specifications regarding appropriate filter material are important for efficient operation. Continuous recording of the temperature of the gas coming into contact with the filter media is made to assure that extended excursions above the recommended value are not occurring. Appropriate corrections are then made immediately, either automatically or by the operator, to maintain inlet temperature within design criteria. This helps minimize the occurrence of extraordinary material breakdown with resultant increased emissions. It also aids in keeping maintenance of the filter in good order and extending the life of the filter material. Measurement technique is similar to that depicted in Section 5.7.1. Figure 5-38 shows the appropriate measurement location.

TABLE 5-8. A GUIDE TO PRESSURE SENSING ELEMENT SELECTION [31]

Selection criteria	Common sensors			Transducers, strain gauges	
	Bourdon	Diaphragm	Bellows	Unbonded	Bonded foil
Pressure range	12 psi to 100 K psi	5 psi to 15 psi	0.5 to 30 psi	0.5 psi through 10 K psi	5 psi through 10 K psi
Temperature range	-40°F to +375°F	-40°F to +375°F	-40°F to +375°F	-320°F to 600°F (0.005%/°F)[a]	-65°F to +250°F (0.01%/°F)[a]
Advantages	Low cost; field replaceable; variety of materials for media and range.	Variety of materials for media and range; field replaceable; large force.	Compact, accurate, field replaceable.	Accepts unidirectional and bi-directional pressure measurements; ac or dc excitation.	Temperature effects small and linear; ac or dc excitation; rugged construction.
Disadvantages	Slow response; large sensor volume sensitive to shock and vibration.	Limited capacity; position sensitive in low ranges.	Limited material; may be position sensitive.	Low signal level (4 mV/V).	Low signal level (3 mV/V) limited temperature range.

(continued)

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[a] Percent/°F over limited compensated range.

TABLE 5-8 (continued)

Selection criteria	Transducers				
	Thin film	Diffused semiconductor	Bonded in semiconductor	Reluctive	Capacitive
Pressure range	15 psi through 5 K psi	1 psi through 10 K psi	5 psi through 10 K psi	0.4 psi through 10 K psi	0.01 through 200 psi
Temperature range	-320°F to +525°F (0.005%/°F)[a]	-65°F to +30,000°F (0.005%/°F)[a]	-65°F to +30,000°F (0.01%/°F)[a]	-320°F to +600°F (0.02%/°F)[a]	0°F to 165°F Requires temperature control.
Advantages	Excellent thermal zero and sensitivity shift; ac or dc excitation.	Small size, high natural frequency; steady and dynamic reliability; repeatability.	Small size, high natural frequency; steady and dynamic; excellent repeatability.	High output (40 mV/V excitation); rugged construction; over pressure capability.	Excellent for low pressure, excellent frequency response; output countable without A/D converter.
Disadvantages	Low natural frequency; low signal level, 3 mV/V.	Susceptible to handling problems; more temperature sensitive than most transducers; electrical output only.	Susceptible to handling problems; more temperature sensitive than most transducers.	Sensor requires ac excitation; susceptible to stray magnetic fields; ac carrier systems require balanced line for data transmission.	Requires short leads from sensor; high impedance output; temperature sensitive; needs extra electronics to produce useable output.

(continued)

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[a] Percent/°F over limited compensated range.

TABLE 5-8 (continued)

Selection criteria	Transducers			
	Potentiometer	Linear variable displacement transformer	Force balance	Piezoelectric
Pressure range	5 psi through 10 K psi	30 to 10 K psi	1 psi through 50 K psi	0.1 psi throuh 10 K psi
Temperature range	-65°F to +300°F nonlinear 0.01%/°F	0°F to 165°F	40°F to 165°F 0.01%/°F	-450°F to 400°F 0.01%/°F
Advantages	Low cost; small size; high output without amplification.	Available in rotary form; not affected by mechanical overload.	High accuracy; high output; stable; wide ranges.	High frequency response; self-generating signal; small size; rugged construction.
Disadvantages	Tendency to short life due to mechanical wear; noise increases with wear.	Some problem maintaining linear movement of core proportional to pressure change; will develop mechanical wear.	Large size; shock and vibration sensitivie; low frequency response.	Temperature sensitive; requires amplifier and special cabling between device and amplifier; slow recovery to shock and overpressure.

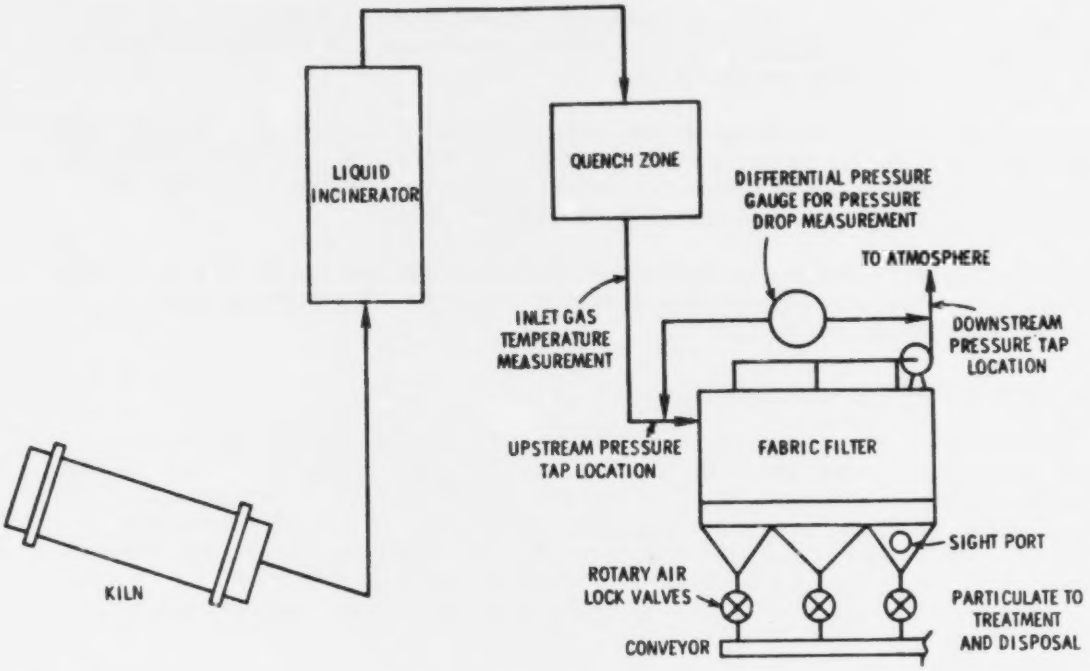
LIQUID INCINERATOR
QUENCH ZONE
DIFFERENTIAL PRESSURE GAUGE FOR PRESSURE DROP MEASUREMENT
TO ATMOSPHERE
INLET GAS TEMPERATURE MEASUREMENT
DOWNSTREAM PRESSURE TAP LOCATION
UPSTREAM PRESSURE TAP LOCATION
FABRIC FILTER
SIGHT PORT
ROTARY AIR LOCK VALVES
PARTICULATE TO TREATMENT AND DISPOSAL
KILN
CONVEYOR

Figure 5-38. Recommended measurement and inspection locations.

5.7.2.2 Gas Flow and Pressure Drop--

Fabric filter collectors are commercially available to handle total gas flows from 100 cfm to greater than a million cfm. The quantity of gas processed and the contaminant concentration in conjunction with specific flow resistance properties of the particulate deposit on the fabric determine the amount of filtration area required for a selected value of operating pressure drop. A design pressure drop is generally chosen around 3 or 4 inches of water for economic reasons, but some units are designed to operate higher than 10 inches of water pressure drop. Variation in the pressure drop over a specified range is normal in fabric filter operation. The operational cycle consists of a gradual buildup of material on the surface of the filter which is periodically cleaned off. The development of this deposition increases the pressure drop with time. This cycle usually remains within specified limits. Continuous recording of the operating pressure drop is maintained by the operator. The pressure drop is maintained within the manufacturer's specified range so that undue disturbance of the design filtration efficiency does not occur. Chapter 4 provides further information regarding fabric filters. The pressure drop measurement device is essentially the same as described in Section 5.7.1.4. Measurement location is shown in Figure 5-38.

5.7.2.3 Residue Generation--

Accumulated particulate matter is removed and transported to a central point for reprocessing or disposal depending on the hazardous nature of the collected material. Means of preventing gas leakage at the hopper discharge is an important design factor. This is normally accomplished through the use of double flap valves or rotary air-lock valves, although the rotary air lock valve will give the most positive seal.

A means of preventing bridging in the hoppers is also important. Common types are mechanical, spring loaded rappers, electric vibrators, and compressed air vibrators. Helicoid screw conveyors are commonly employed for horizontal transport of the collected material to a central point.

Residue analysis is needed to ascertain the hazardous nature of the collected material and to select appropriate disposal options. The type of such analyses is covered in Chapter 3.

5.7.3 Electrostatic Precipitators

Precipitators are theoretically complex control devices which are almost always specifically designed for a given application. Many technical considerations are evaluated initially to aid the applicability determination [33]. In each case, however, a set of operating conditions and checkpoints are defined by the vendor as proper and necessary to maintain the design removal efficiency. Compliance with these and other conditions pertinent to maintaining the quality of the environment are evaluated; the following information serves as a checklist for such items.

5.7.3.1 Rapping Cycle Practice--

Precipitators use a "rapping" or force impact sequence to remove buildup of collected material on the internal surfaces of the equipment. This causes re-entrainment of collected material in the exhaust gas stream which affects precipitator removal efficiency. Three variables are involved; the rapping interval, the rapping intensity, and the duration of the rapping cycle.

(1) Rapping interval - It is desirable to know the time interval of rapping for each electrode in the precipitator field, because the upstream fields are normally rapped more frequently than the downstream fields as a result of the relatively high material buildup in the initial stages.

(2) Rapping intensity - How hard an electrode is rapped will affect the amount of material removed each rap.

(3) Cycle duration - How long a time the rap covers affects the degree of "cleanliness" achieved.

The intervals for these three variables are designed to be appropriate for the application. This choice is normally based on the experience of the company with their product. Common practice ranges from very frequent rapping (every few minutes) to intervals as long as an hour. The intensity may range from low to high with frequent intervals, but is normally high at longer intervals. The ability to change the values is normally a part of the precipitator controls. A check of the proper settings is made at least once a day by the operator and records kept for examination by the EPA upon request. A typical rapping mechanism is shown in Figure 5-39.

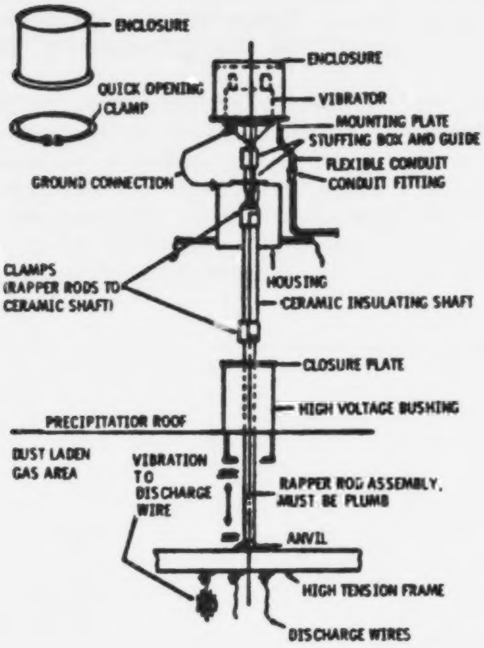
ENCLOSURE
ENCLOSURE
QUICK OPENING CLAMP
VIBRATOR
MOUNTING PLATE
STUFFING BOX AND GUIDE
FLEXIBLE CONDUIT
GROUND CONNECTION
CONDUIT FITTING
CLAMPS (RAPPER RODS TO CERAMIC SHAFT)
HOUSING
CERAMIC INSULATING SHAFT
CLOSURE PLATE
HIGH VOLTAGE BUSHING
PRECIPITATION ROOF
DUST LADEN GAS AREA
VIBRATION TO DISCHARGE WIRE
RAPPER ROD ASSEMBLY, MUST BE PLUMB
ANVIL
HIGH TENSION FRAME
DISCHARGE WIRES

Figure 5-39. Typical vibratory rapper.

5.7.3.2 Temperature, Resistivity, and Gas Moisture Effects--
The resistivity of the material collected can have an influence on the collection efficiency. If the resistivity is greater than about 5 x 10^{10} ohm-cm, the electrical field developed in the collected particle layer can exceed the breakdown field strength. Excessive spark rates and back corona can occur which will cause operation at lower than normal current densities with resulting degraded performance. If the particle resistivity is less than about 10^7 ohm-cm, the electrical forces holding the material to the collection plates may be low. Excessive re-entrainment can occur yielding lower performance.

A resistivity range showing the allowable span for maintenance of removal efficiency is normally supplied with an ESP along with a measurement of the resistivity of the material collected. As long as the feed material does not change, no further check on the resistivity is usually necessary, unless removal efficiency changes for no apparent cause.

Increasing moisture content will also lower the resistivity. A change in moisture content will normally only occur with a change in the feed material moisture or a change in steam injection conditions if such a technique is used to increase hydrogen ion availability in the combustion zone.

Temperature affects precipitator removal efficiency although not as much as it affects baghouses and wet scrubbers. Temperature considerations are normally evaluated during the design phase of the precipitator by the vendor.

Specifications are provided by the owner/operator showing the allowable temperature range for design removal efficiency. Continuous recording of the incoming gas temperature is made by the owner/operator to assure that extended excursions above or below the recommended range are not occurring. Appropriate corrections are then made to maintain inlet temperature within design criteria. The measurement technique must be similar to that discussed in Section 5.7.1. Figure 5-40 shows the appropriate measurement location.

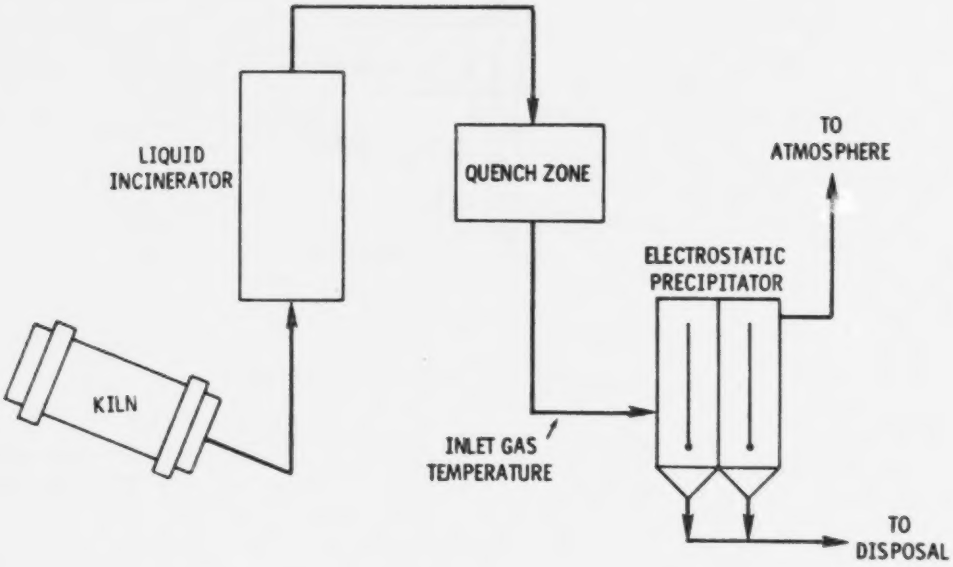

Figure 5-40. Recommended measurement location.

5.7.3.3 Applied Voltage (Power Supply Control)--

The overall objective of precipitator design is to combine the component parts into an effective arrangement that results in optimum collection efficiency. A very important aspect toward this objective is the design of the precipitator power supply.

The power supply normally consists of four components as shown in Figure 5-41; a step-up transformer, a high voltage rectifier, a control element, and a sensor for the control system. A step-up transformer is required because the operating voltages (applied voltage) range from about 20 to 100 KV. This system is used to maintain the applied voltage at an optimum value even when the material characteristics and concentration exhibit temporal fluctuations.

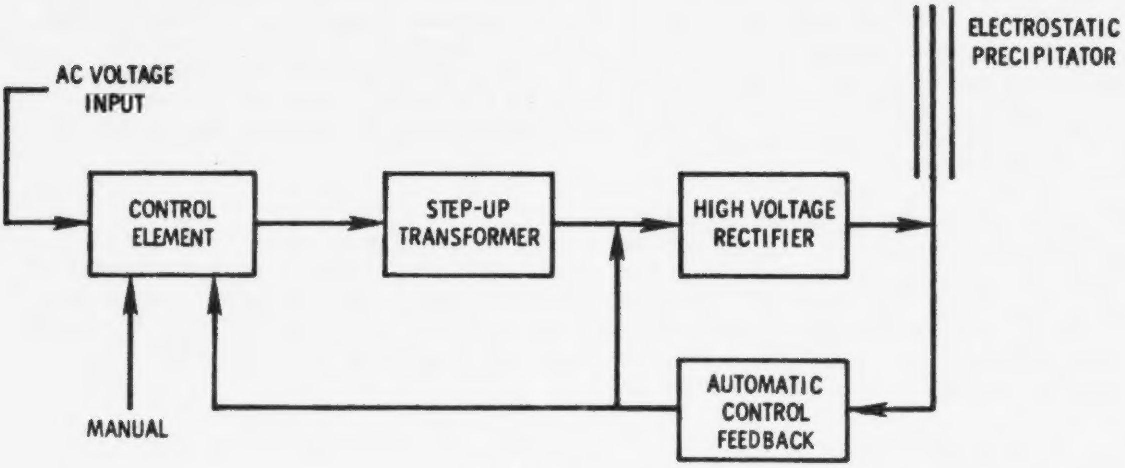

Figure 5-41. Power supply system for modern precipitators.

Once normal operating conditions have been established, continuous monitoring of the power supply system is typically maintained. The necessary indicators (meters) for this are normally provided as part of the precipitator control panel. Deviations will likely be caused by excessive buildup of collected material in the precipitator or breakdown of the electrical supply circuitry. Investigation should begin immediately to locate the cause, and correction made, including shut off of feed material and/or shut down for repair if removal efficiency drops below specifications.

5.7.3.4 Gas Flow--

Changes in the gas flow rate can affect removal efficiency. This becomes more critical as the particles get smaller. The precipitator is designed so that the combination of the forces applied on the particles and the time that the forces remain on the particle (dwell time) result in the movement of the particles to a collection surface. The smaller the particle, the longer it takes under fixed conditions to do this.

If the gas flow rate increases beyond design capacity, this combination becomes compromised and a degradation of removal efficiency will occur.

The gas flow measurement requirement discussed in Section 5.7.3 is appropriate for checking the precipitator flow parameter also. Sustained increase in the gas flow is usually checked immediately for effect on the design removal efficiency, and correction made to remain within design conditions. This may require reduction in input feed material flow or some other modification(s).

5.7.3.5 Residue Generation Rate and Dust Removal Capacity--

It is important to determine that the dust removal system remains working properly according to specifications. Hoppers are used to collect material removed from the collecting surfaces by the rapping sequence. If the residue generation rate exceeds the material removal capacity, re-entrainment of collected material will occur, greatly reducing precipitator efficiency. Historically, automatic removal of collected material is one of the major causes of precipitator failure, and daily inspection for proper operation is typically required.

5.7.3.6 Internal System Pressure--

If the precipitator system is operated with internal pressures less than ambi-ent, leakage of air through the hopper can also cause a re-entrainment of mate-rial from the hoppers. A design check to make sure the hopper area is properly sealed is made to prevent such occurrence. Section 5.7.2.3 discusses appropriate seal techniques. Further details regarding electrostatic precipitators is found in Chapter 4.

5.7.4 Mist Eliminators

Mist eliminators are extensively employed to reduce emissions of entrained liquid droplets from wet scrubbers. The most commonly used types include cyclone collectors, simple inertial separators such as baffles, wire mesh mist eliminators, and fiber bed elminators. In use, the latter three devices work by the same principle. Rising mist droplets strike the mist eliminator, coalesce due to inertial impaction and direct interception, and form larger droplets which fall back into the scrubber.

Cyclones differ from the other types of mist eliminators because centrifugal force is used to remove the droplets. The particulates, because of their inertia, tend to move toward the outside wall from which they are led to a receiver [22].

The choice of mist eliminator equipment is dependent on droplet size, gas flow pressure drop, and cost considerations. Cyclone collectors are used to remove larger droplets (10 to 100 μm range), and are used commonly in conjunction with venturi scrubbers. Simple inertial mist eliminators (baffle, louvre, and vane-type among others) are effective with droplets about 10 μm in size. Fiber bed mist eliminators have the highest efficiency of any of the types of eliminators for trapping very fine droplets (as small as 0.5 μm).

Although the different types of mist eliminators vary in design, they have common parameters which must be monitored to evaluate operational effectiveness. These are detailed below.

5.7.4.1 Temperature--

Excessive temperatures can adversely effect the performance of a mist eliminator. Higher temperatures could result in a heavier loading and increased corrosion. Since the mist eliminator is located downstream from the wet scrubber, monitoring the temperature of the scrubber is sufficient to ensure the mist eliminator is operating at a suitable temperature.

5.7.4.2 Gas Flow and Pressure Drop--

For maximum efficiency, flow of gases through the mist eliminator should be high enough to be practical while allowing a reasonable retention time. Re-entrainment of the liquid droplets can result if the gas flow is too high. The optimum gas flow varies according to the particulate mist eliminator used, and is normally supplied by the manufacturer. Pressure drop may vary from 2 to 12 in. of water gage, in accordance with manufacturers' specifications.

Continuous recording of the operating pressure drop is typically maintained by the owner/operator and such records made available for inspection. A change in the pressure drop would indicate a change in the gas flow rate or, more importantly, the accumulation of solids in the equipment, decreasing its efficiency.

5.7.4.3 pH Level--

To prevent excessive corrosion, the mist eliminator is normally constructed of material that is resistant to the pH level of the mist. pH is monitored in the wet scrubber to ensure the mist eliminator is operating within the manufacturer's recommended pH range.

5.7.4.4 Maintenance--

Proper maintenance of mist elimination equipment is essential in order to maintain optimal efficiency, for collection of solid material in the equipment can decrease efficiency. The equipment can be cleaned by backwashing or by automatic spray devices. Often, daily inspection is required to assure that the backwash system is operating properly.

5.8 SCRUBBER WASTE STREAM TREATMENT INSPECTION AND MONITORING

5.8.1 Flow Measurement and Monitoring

In any treatment system unit operation, the measurement and/or control of flow is a critical parameter. In this case, flow is a factor in determining the rate of caustic solution addition in the neutralization system. Flow measuring and recording devices are described in detail in Section 5.7.1.2.

5.8.2 Flow Control

Automatic monitoring systems are employed to provide advanced warning when the water level in the neutralization system has increased above a set operating limit. This enables operators to institute immediate process alterations to allow the neutralization system to equilibrate back to normal operations.

5.8.3 pH Monitoring

Sensors for automatic monitoring, recording, and control of pH are especially sensitive to process interferences. It is necessary, therefore, that care is taken in the selection of automatic equipment in order to ensure that it will function satisfactorily in the treatment scheme.

Automatic monitoring of pH has the following advantages:

(1) pH is recorded on a continuous basis, producing a clear picture of variation with time.

(2) Time lag between sampling and analysis is much shorter than in manual sampling. Problems resulting from the storage of sampling equipment are also eliminated.

(3) The rate of neutralizing chemical addition can be continuously controlled.

(4) Automatic monitoring can be combined with an alarm system to provide warning if the neutralized effluent is of insufficient quality. When this occurs, a by-pass valve could be opened to direct the effluent to a storage basin for gradual addition to the treatment system once normal operations have been resumed.

Automatic monitoring is not without disadvantages, however. Among them are:

(1) The sensor may not be capable of registering unusual circumstances due to probe location.

(2) The wastewater characteristics, at least in general, must be known in advance of monitoring equipment selection.

(3) The initial cost of automatic equipment is relatively high.

Problems which can be anticipated and need to be addressed in system design and operation are:

(1) Loss of calibration. Regular maintenance is necessary to prevent errors.

(2) Bacterial growth may inhibit sensor operation. Regular cleaning is necessary unless self-cleaning sensors are used.

(3) Mechanical damage may occur if the probe is unprotected by a screen, similar device, or design.

(4) Miscellaneous problems resulting from power failures, mishandling of equipment, pump difficulties, etc.

(5) Interferences should be analyzed and addressed before equipment selection and installation.

5.8.4 pH Control Systems

A pH control system consists of a pH electrode probe, located in the flow scheme, connected to a controller which reports to a recorder. The controller regulates the rate of neutralization chemical addition.

In the monitoring/control system, several types of valves may be used, depending on the consistency of the influent quality and the treatment chemicals used. The types of controllers likely to be employed are on-off, proportional, resetting derivative, and flow-proportional.

5.8.4.1 On-Off Controller--

The on-off controller is the least expensive of the above devices. If the pH exceeds, in either direction, a certain limiting value, the valve opens and neutralizing agent is added until an established corrected value is achieved. This system has limited application here due to the potential for large chemical overdose.

5.8.4.2 Proportional Controller--

Proportional controllers are more advanced than on-off controllers and are used where a more constant effluent quality is desired. In its simplest application, the proportional controller regulates the amount of neutralizing solution in proportion to a deviation from a set point as a means of controlling pH within an acceptable range.

5.8.4.3 Resetting Derivative Controller--

A resetting derivative controller regulates the speed with which the valve opens to add neutralizing agent. The valve speed is based on the rate of derivation from a set point. This system does not typically operate well with high suspended solids effluent, however.

5.8.4.4 Flow Proportional Controller--

If the influent water quality is constant, but flow varies, the neutralization control valve may be connected to a flow meter rather than the pH probe. Neutralizing agent will be added proportional to the flow.

A schematic of the general elements in a pH control system using lime is given in Figure 5-42.

5.8.5 Scrubber Solution pH Control

The particulate removal efficiency of a venturi scrubber and the acid gas scrubbing efficiency of a packed tower is affected by maintenance of the pH of the incoming scrubbing solution.

If a recirculating mode is utilized, the incoming stream must be neutralized after contact with the gas. Neutralization is necessary to prevent corrosion of metal surfaces, construction materials, and tower packing.

The process of neutralization is the interaction of an acid with a base. The typical properties exhibited by an acid in solution are due to the concentration of the hydrogen ion, (H^+). Alkaline (basic) properties are the result of the concentration of hydroxyl ion (OH^-). In an aqueous solution, acidity and alkalinity are defined with respect to pH, where $pH = -\log [H^+]$, or as $pH = 14 + \log [OH^-]$. Neutralization is typically the adjustment of pH from one extreme to a range of pH 6.0 to 8.5.

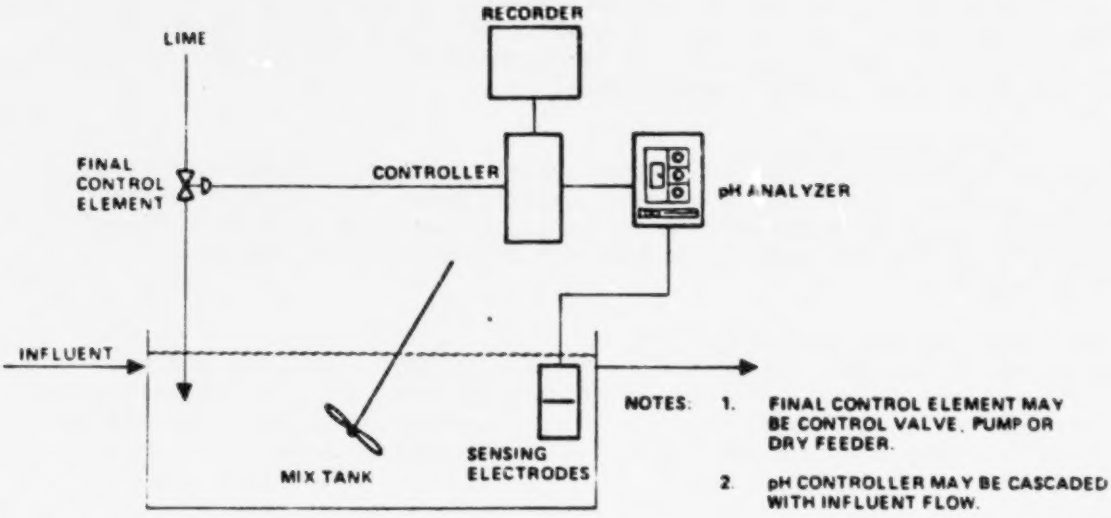
RECORDER
LIME
FINAL CONTROL ELEMENT
CONTROLLER
pH ANALYZER
INFLUENT
MIX TANK
SENSING ELECTRODES
NOTES: 1. FINAL CONTROL ELEMENT MAY BE CONTROL VALVE, PUMP OR DRY FEEDER.
2. pH CONTROLLER MAY BE CASCADED WITH INFLUENT FLOW.

Figure 5-42. Elements of a typical pH control system.

The scrubber and absorber solutions will, after contact with acid gases, be acidic in nature, ($pH < 7$). Neutralization is accomplished by the addition of an alkaline material, such as caustic soda (NaOH). An example of the neutralization process is the reaction between hydrochloric acid and sodium hydroxide:

$$HCl + NaOH \rightarrow H_2O + NaCl$$

The product, sodium chloride in aqueous solution, is neutral with $pH = 7.0$.

Neutralization is usually accomplished by contacting the incoming feed with concentrated caustic or acid solution in a well mixed chamber.

Lagoons, concrete basins, chemically resistant tanks, and in-line static mixers are all used for this purpose.

Neutralized water can be piped to storage ponds for subsequent process reuse, solar evaporation, or further treatment, if necessary for NPDES discharge.

A simple schematic of a two-step neutralization system is given in Figure 5-43.

5.9 CONTINUOUS MONITORING INSTRUMENTATION FOR GASEOUS COMPONENTS

Continuous monitoring of at least O_2, CO, and CO_2 gases in the exhaust stream of hazardous waste incineration are proposed. A number of continuous monitoring systems are available for this general purpose. These monitors are automated, and are capable of unattended operation for days or weeks. While such instruments have been successfully applied to measuring CO, CO_2, and O_2 in combustion gases, their accuracy remains somewhat controversial within both the technical community and users.

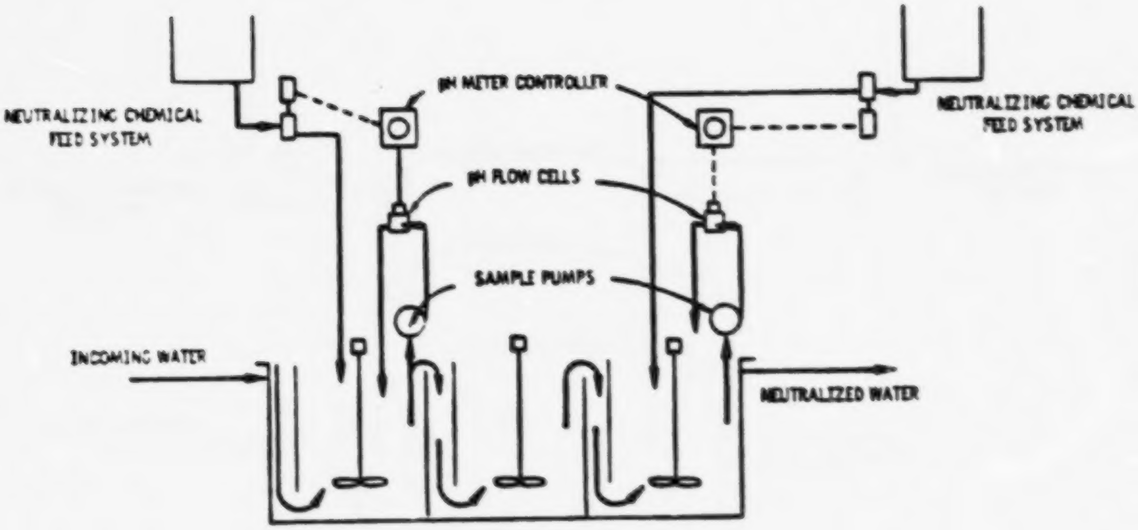
NEUTRALIZING CHEMICAL FEED SYSTEM
pH METER CONTROLLER
NEUTRALIZING CHEMICAL FEED SYSTEM
pH FLOW CELLS
SAMPLE PUMPS
INCOMING WATER
NEUTRALIZED WATER

Figure 5-43. Two-step neutralization flow schematic.

The following text provides a summary of aspects pertinent to the evaluation. Should greater detail be desired, the permit writer is encouraged to consult the EPA Handbook of Continuous Air Pollution Source Monitoring Systems, EPA-625/6-79-005, from which most of the following information is derived [34].

The basic elements of a pollutant monitoring system are shown in Figure 5-44.

5.9.1 Available Systems

Proposed continuous monitoring systems will likely fall into one or more of the following types:

- Nondispersive infrared analyzers (NDIR)
- Polarographic analyzers
- Paramagnetic analyzers
- Nondispersive ultraviolet analyzers (NDUV)
- Electrocatalytic analyzers

Table 5-9 summarizes what component each type of analyzer is capable of measuring.

In addition to being categorized according to detection type, a broader classification of monitoring systems exists which distinguishes between extraction and in-stack or in-situ type systems. All five of these instruments with the exception of the polarographic monitor, are available in both extractive and in situ types.

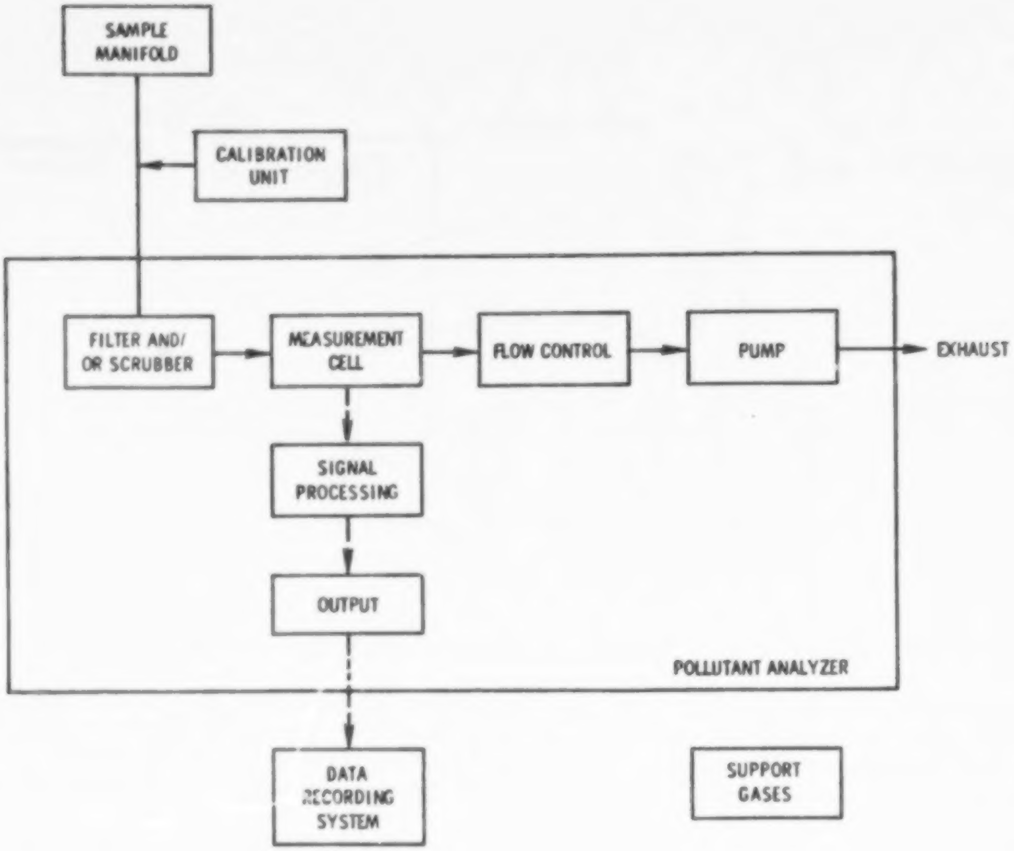
SAMPLE MANIFOLD
CALIBRATION UNIT
FILTER AND/ OR SCRUBBER
MEASUREMENT CELL
FLOW CONTROL
PUMP
EXHAUST
SIGNAL PROCESSING
OUTPUT
POLLUTANT ANALYZER
DATA RECORDING SYSTEM
SUPPORT GASES

Figure 5-44. Elements of pollutant monitoring system.

TABLE 5-9. ANALYZERS CAPABLE OF MEASURING GASEOUS COMPONENTS

Detection device	Component O_2	 CO_2	 CO
NDIR		X[a]	X[a]
NDUV		X	X
Paramagnetic	X		
Polarographic	X	X	X
Electrocatalytic	X[a]		

[a] Most typically used.

Discussions of the components, advantages and disadvantages, and limitations of both extractive and in-situ versions follow. The general principles of operation discussed for the analyzers themselves may be applied to either version, as the differences in the detector mechanics are subtle.

5.9.1.1 Extractive Systems--

The ability of an extractive, or remote monitoring system, to provide reliable data depends upon a properly designed sampling interface. The total extractive system must perform several functions:

- Remove a representative gas sample from the source on a continuous basis.
- Maintain the integrity of the sample during transport to the analyzer (within specified limits).
- Condition the sample to make it compatible with the monitor analytical method.
- Allow a means for a reliable calibration of the system at the sampling interface.

The design of the sampling interface, including the components used in its construction, will depend on the characteristics of both the source gas stream and the monitoring instrument.

The design of a sampling interface requires that the system deliver a conditioned, continuous gas sample to the gas analyzer. A number of different interface designs may be able to perform this task at a given source. The actual system designed for a specific source generally incorporates a variety of trade-offs based on source/analyzer requirements and financial restraints. A system typically will include the following components:

- In-stack sampling probe
- Coarse in-stack filter
- Gas transport tubing
- Sampling pump
- Moisture removal system
- Fine filter
- Analyzer
- Calibration system
- Data recorder

Sampling Probe--Representative gas sampling requires samples that will demonstrate the total pollutant gas emissions from a source. The temperature and velocity traverse across the duct may indicate a necessity for a multipoint probe to extract samples from numerous points across the entire duct. Several research studies have shown that, although gas concentration cannot be assumed to correspond directly to temperature and velocity gradients in a duct, these measurements are excellent indications for positioning gas sampling probes. This research has shown that a representative gas sample may be extracted from a grid of equal areas laid out in the duct. A temperature and velocity traverse is then performed in each row of the grid. The multipoint gas sampling probe is then positioned across the row that indicated temperature and velocity readings closest to the average reading in the duct.

Gas sampling requires that particulate matter, which can harm the analyzer and shorten the operating life of the sample pump, be removed from the gas stream. Directing the probe inlet countercurrent to the gas flow helps prevent many large particulates from entering the system. Particulates that enter the probe can be removed by coarse and fine filters.

Coarse Filters--The coarse filter is usually located at the probe tip in the stack, where it then can prevent particulate matter from plugging the sampling probe and will not require heat tracing to prevent moisture condensation. There are two general types of coarse in-stack filters: external or internal.

The external coarse filter is a porous cylinder, typically constructed of sintered 316 stainless steel, though it may also be glass, ceramic, or quartz. It is essential that the porous cylinder be protected by a baffle to prevent excessive particulate buildup on the leading edges. These porous cylinders have an expected utility of approximately 2 to 3 months before they become clogged with particulate, depending on the sampling rate. Although they can be regenerated by back flushing, they eventually need replacing. The nominal cost (~\$25) suggests that it may be easier to replace the filter on a routine basis than to install costly automatic backflushing equipment.

Filter material is available from a number of manufacturers. Glass wool filters have been used in some experiments; however, they have a higher pressure drop than the Alundum thimble.

Fine Filters--The majority of extractive stack gas analyzers require almost complete removal of all particles larger than 1 micron from the gas stream. This is best accomplished by including a fine filter near the analyzer inlet. Fine filters are divided into two broad categories: surface filters and depth filters.

Surface filters remove particulates from the gas stream using a porous matrix. The pores prevent penetration of particulates through the filter, collecting them on the surface of the filter element. Surface filters can remove particulates smaller than the actual filter pore size with particulate cake buildup and electrostatic forces acting to trap smaller particles. These filters perform well on dry, solid particulates without excessive pressure drop. A surface filter will foul quickly if it becomes wet or if the particulate is gummy.

Depth filters collect particulates within the bulk of the filter material. A depth filter may consist of loosely packed fibers or relatively large diameter granules. These filters perform well for gummy solids or moist gas streams and dry solids. In the case of malfunction, their flexibility can protect the analyzer from damage. Glass wool packed to a density of 0.1 gm/cm^3 and a bed depth of at least 2 inches can act as an inexpensive depth filter for normal gas flowrates. These filters must be carefully packed to avoid channeling.

Gas Transport Tubing--The gas tubing or sample lines transport the extracted gas sample from the stack through the interface system and into the analyzer. When evaluating sampling lines, it is important to consider:

- Tube interior-exterior diameter
- Corrosion resistance
- Heat resistance (for lines near high temperature areas or heat tracing)
- Chemical resistance to gases being sampled
- Cost

The gas tubing is sized to ensure an adequate gas flowrate with a reasonable pressure drop and good system response time. A flowrate of 2 standard liters per minute (enough to supply two gas analyzers) through a 6.35-mm OD (1/4 in.) tubing exhibits a pressure drop between 1 and 3 mm Hg per 30.48-m length. This pressure drop is quite acceptable for most sampling pumps. The response time (t) for a sampling line volume (V) can be calculated at a flowrate (F) in the equation:

$$t = \frac{V}{F} \text{ (assuming no axial dispersion or wall effects)}$$

At a flowrate of 1 standard liter minute, the response time for a 30.48-m tube section at 25°C and pressure drop of 152 mm Hg is only 30 seconds. These data indicate that 6.35-mm OD tubing is acceptable for sampling lines [31].

Teflon® and stainless steel exhibit excellent corrosion and heat resistance in addition to being chemically inert to stack gases and acid mist. The corrosion resistance of stainless steel is enhanced by keeping gases above the dew point. These materials are commercially available in heat traced form. Teflon® is normally recommended for out-of-stack heat traced lines; stainless steel is a good material for in-stack lines. Polypropylene and polyethylene lines exhibit good chemical resistance (except to nitric acid). Plastic lines are a good, economical choice for sampling lines that carry dry gas and are maintained above the freezing point without heat tracing. A reliable, effective, and economical sampling line system probably would incorporate stainless steel, Teflon®, and plastic.

Sampling Pump--A diaphragm or bellows pump upstream of the analyzer is superior to other pump types for gas handling. The primary advantages offered are:

- No shaft seal required.
- No internal lubrication required.
- Pumps are relatively inexpensive.
- Adequate suction and discharge pressures are developed at flowrates well above those needed for gas sampling systems.

Some sampling interface systems may place the pump downstream of the analyzer, pulling the sample through the system. This could allow the use of an aspirator pump without moving parts. Pressure drop at the analyzer would be higher, but for some analyzers with built-in pressure regulators, this may be preferable arrangement. Downstream pumps increase the potential for air leaking in and, in the case of aspirator pumps, require a source of large quantities of compressed air, steam, or water.

Moisture Removal--Stack gases may contain significant quantities of water and acid vapor. A limited number of analyzers are not affected by the presence of water vapor in the sample (e.g., a differential absorption ultraviolet instrument). These analyzers do, however, require that gases be kept above the dew point to protect against condensation and corrosion within the analyzer. Other analytical methods that are affected by water vapor require moisture removal. Generally, the gas is dried to a low constant level of moisture content for both stack gases and calibration gases. Refrigerated condenser traps or permeation dryers are commonly used for moisture and acid removal.

Sampling Interface Monitor Calibration--The entire sampling interface and monitor must be calibrated as a unit. The calibration gases enter the continuous gas monitoring system as near as possible to the same entrance point for the stack gas. This is essential to check the entire system. The analyzer is then calibrated at the same gas flowrate, pressure, temperature, and operating procedure used in monitoring the stack gas. Flooding the coarse filter with calibration gas at the probe inlet or using a check valve that allows calibration gas injection directly behind the coarse filter are the best methods for accomplishing this calibration. Calibration in this manner assures that any leaks, blockage, or sorption of gases taking place in the system will be discovered. The importance of this method cannot be overemphasized. Automatic gas injection systems are easily constructed with electric solenoid valves.

The calibration gases are typically checked with triplicate runs of the reference method procedure for that gas. All runs of the reference method must agree with the average for the three runs within 20% or they must be repeated. The gas analysis is repeated every six months. Although many manufacturers certify a longer shelf life, experience has shown that manufacturer calibration gas certification is subject to error.

EPA is currently studying the option of using National Bureau of Standards (NBS) calibration gases or gases traceable to NBS standards, instead of requiring reference method analyses. NBS gases are relatively accurate and stable but are more expensive than commercial gases.

Controlling the Sampling Interface/Monitor System--The best system does not require elaborate control mechanisms. The necessary controls are easily installed and maintained by owner/operator personnel. The suggested controls include the following:

- Temperature control at the cold end of the heated sample line. This is to ensure that the gases are above freezing to protect the lines from fracture or blocking. Temperature is also controlled at the refrigerated condenser to maintain moisture removal efficiency.

- Pressure control is needed at the pump discharge to protect the pump. The pressure drop across the fine filter is monitored to protect the analyzer and to ensure proper system function (most analyzers are sensitive to pressure changes).

- Gas flowrate control is installed to make certain the analyzer receives the correct gas flow. This is not critical, since most analyzers are relatively insensitive to minor flowrate change.

- Calibration gas valving automatically injects calibration gases once every 24 hr. This can be accomplished with a simple electric solenoid valve. The calibration gases should flow through the sampling system at the same condition of temperature, pressure, and flow as does the stack gas.

5.9.1.2 In-Situ Monitoring Systems--
The problems and expense associated with extractive monitoring systems have led to the development of instrumentation that can directly measure source-level gas concentrations in the stack. The so-called in-situ systems do not modify the flue gas composition and are designed to detect gas concentrations in the presence of particulate matter. Since particulate matter causes a reduction in light transmission, in-situ monitors utilize advanced electro-optical techniques to eliminate this effect when detecting gases.

Cross-stack in-situ monitors measure a pollutant level across the complete diameter or a major portion of the diameter of a stack or duct. Stratification effects are lessened by the use of cross-stack instruments, since an average reading is taken over a relatively long sample path. There are two types of cross-stack monitors: single pass and double pass.

- Single-pass systems locate the light transmitter and the detector on opposite ends of the optical sample path. Since the light beam travels through the flue gas only once, these systems are termed single pass.

- Double-pass systems locate the light transmitter and the detector on one end of the optical sample path. To do this, the light beam must fold back on itself by the use of retroreflector. The light beam will traverse the sample path twice in going from the instrument housing to the retroreflector and back to the instrument. Double-pass systems are easier to service than single-pass systems, since all of the active components are in one location.

In-stack in-situ systems monitor emission levels by using a probe that measures over a limited sample pathlength. All of the commercial, optical in-stack monitors are double-pass systems.

In principle, currently marketed cross-stack gas analyzers present many advantages over extractive monitoring systems. A cross-stack system may allow greater flexibility in site selection, since an average sample reading is taken over a relatively long path. It should be noted, however, that gas stratification in a duct or stack is a two-dimensional phenomenon, not one-dimensional. A cross-stack monitor can linearly average concentrations over its measuring path, but does not properly weigh the contributions of stratified areas to the measurement. For severe cases of stratification, the problem of obtaining representative concentration values may be comparable to the problems encountered by point monitors.

One of the principal marketing features of cross-stack analyzers is that a single instrument can monitor a number of gases and even opacity. The cost of such a monitor can be comparable to the purchase price of three or four separate instruments combined in an extractive system.

There are, however, a number of disadvantages associated with the cross-stack monitors. An in-situ cross-stack monitor can monitor only one flue or stack at a time. Costs might be prohibitive if a number of stacks must be monitored. In such a case, multiple probes and sampling lines leading into a single extractive system might be the better choice. Problems with optical misalignment, vibration affecting the optical systems, and the failure of electronic components also can occur. It is common among vendors of these instruments to offer service packages whereby the systems are periodically checked by a company serviceman. A service package generally will ensure that a system will continue to function, but the cost involved may bring the operating expenses to a level comparable to that of an extractive system.

5.9.2 Analyzers

5.9.2.1 NDIR Analyzers--

Nondispersive infrared (NDIR) analyzers have been developed to monitor SO_2, NO_x, CO, CO_2, and other gases that absorb in the infrared, including hydrocarbons. NIDR instruments utilize a broad band of light that is centered at an absorption peak of the pollutant molecule.

This broad band is usually selected from all the light frequencies emitted by the infrared source by using a bandpass filter. Table 5-10 gives the band centers for several of the gases found in source emissions.

In a typical NDIR analyzer, infrared light from a lamp or glower passes through two gas cells--a reference cell and a sample cell. The reference cell generally contains dry nitrogen gas, which does not absorb light at the wavelength used in the instrument. As the light passes through the sample cell, pollutant molecules will absorb some of the infrared light. As a result, when the light emerges from the end of the sample cell, it will have less energy than when it entered. It also will have less energy than the light emerging from the reference cell. The energy difference is then sensed by some type of detector, such as a thermistor, a thermocouple, or microphone arrangement.

The advantages of the NDIR-type analyzers are their relatively low cost and the ability to apply the method to many types of gases. Generally, a separate instrument is required for each gas, although several instruments have interchangeable cells and filters to provide more versatility. Problems associated with the method are those that arise from interferring species, the degradation of the optical system caused by corrosive atmospheres, and in some cases, limited sensitivity. The microphone type detectors are sensitive to vibration and often require both electronic and mechanical damping, for example, by placing the instrument on a foam insulation pad.

5.9.2.2 Nondispersive Ultraviolet Analyzers (NDUV)--

Several available nondispersive systems use light in the ultraviolet and visible regions of the spectrum rather than in the infrared. Essentially, the

TABLE 5-10. INFRARED BAND CENTERS OF SOME COMMON GASES

Gas	Location of band centers, μm	Wave number, cm^{-1}
NO	5.0 - 5.5	1,800 - 2,000
NO_2	5.5 - 20	500 - 1,800
SO_2	8 - 14	700 - 1,250
H_2O	3.1	1,000 - 1,400
	5.0 - 5.5	1,800 - 2,000
	7.1 - 10	3,200
CO	2.3	2,200
	4.6	4,300
CO_2	2.7	850 - 1,250
	5.2	1,900
	8 - 12	3,700
NH_3	10.5	950
CH_4	3.3	1,300
	7.7	3,000
Aldehydes	3.4 - 3.9	2,550 - 2,950

analyzers measure the degree of absorption at a wavelength in the absorption band of the molecule of interest. This is similar to the NDIR method, but the major different is that a reference cell is not used. Instead, a reference wavelength, in a region where the pollutant has minimal absorption, is utilized.

This method of analysis is often differential absorption, since measurements are performed at two different frequencies. This method is not limited to extractive monitoring systems, but it also is used in both in-situ analyzers and remote sensors. As with all extractive monitoring systems, particulate matter is removed before entering the analyzer. It is not necessary, however, to remove water vapor in some of these systems. A heated sample line and heated cell prevent condensation in the analyzer. Since water does not absorb light in this region of the ultraviolet spectrum, no interference occurs.

5.9.2.3 Polarographic Analyzers--

Polarographic analyzers have been called voltammetric analyzers or electrochemical transducers. With the proper choice of electrodes and electrolytes, instruments have been developed utilizing the principles of polarography to monitor SO_2, NO_2, CO, O_2, H_2S, and other gases.

The transducer in these instruments is generally a self-contained electrochemical cell in which a chemical reaction takes place involving the pollutant molecule. Two basic techniques are used in the transducer: (1) the utilization of a selective semipermeable membrane that allows the pollutant molecule to diffuse to an electrolytic solution, and (2) the measurement of the current change produced at an electrode by the oxidation or reduction of the dissolved gas at the electrode.

The electrolyte of the cell generally will be used up in 3 to 6 months of continuous use. The cells can be sent back to the company and recharged, or new ones can be purchased. It is extremely important that the sample gas be conditioned before entering these analyzers. The stack gas will come to ambient temperature, and the particulate matter and water vapor are removed to avoid fouling the cell membrane.

5.9.2.4 Electrocatalytic Oxygen Analyzers--

A new method for the determination of oxygen has developed over the past several years as an outgrowth of fuel-cell technology. These so-called fuel-cell oxygen analyzers are not actually fuel cells, but simple electrolytic concentration cells that use a special solid catalytic electrolyte to aid the flow of electrons. These analyzers are available in both extractive and *in-situ* (in-stack) configurations. This versatility of design is making them popular for monitoring diluent oxygen concentrations in combustion sources.

In basic electrochemistry, one of the common phenomena studied is the flow of electrons that can result when two solutions of different concentrations are connected together. The electron flow results from the fact that the chemical potential is different on each side and that equilibrium needs to be reached. There are two half-reactions that take place in this example.

The instruments designed to continuously monitor oxygen concentrations utilize different concentrations of oxygen gas expressed in terms of partial pressures. A special porous material, zirconium oxide, serves both as an electrolyte and as a high temperature catalyst to produce oxygen ions.

If the temperature is well stabilized and the partial pressure of the oxygen on the reference side is known, the percentage of oxygen in the sample can be easily obtained.

One problem with the method is that carbon monoxide, hydrocarbons, and other combustible materials will burn at the operating temperature of the device. This will result in a lowering oxygen concentration in the sample cell, which, however, would be insignificant for concentrations of the combustible materials on the ppm level.

5.9.2.5 Paramagnetic Oxygen Analyzers--

Molecules will behave in different ways when placed in a magnetic field. This magnetic behavior will be either diamagnetic or paramagnetic. Most materials are diamagnetic and when placed in a magnetic field will be repelled by it. A few materials are paramagnetic; they are attracted by a magnetic field. Paramagnetism arises when a molecule has one or more electrons spinning in the same direction. Most materials will have paired electrons; the same number of electrons spinning counterclockwise as spinning clockwise. Oxygen, however, has two unpaired electrons that spin in the same direction. These two electrons give the oxygen molecule a permanent magnetic moment. When an oxygen molecule is placed near a magnetic field, the molecule is drawn to the field and the magnetic moments of the electrons become aligned with it. This striking phenomenon was first discovered by Faraday and forms the basis of the paramagnetic method for measuring oxygen concentrations.

There are two methods of applying the paramagnetic properties of oxygen in the commercial analyzers. These are the magnetic wind or thermomagnetic methods and the magnetodynamic methods:

- Magnetic Wind Instruments (Thermomagnetic)--The magnetic wind instruments are based on the principle that paramagnetic attraction of the oxygen molecule decreases as the temperature increases.

  Several problems can arise in the thermomagnetic method. The cross-tube filament temperature can be affected by changes in the thermal conductivity of the carrier gas. The gas composition should be relatively stable if consistent results are desired. Also, unburned hydrocarbons or other combustible materials may react on the heated filaments and change their resistance.

- Magneto-dynamic Instruments--The magneto-dynamic method utilizes the paramagnetic property of the oxygen molecule by suspending a specially constructed torsion balance in a magnetic field. When a sample containing oxygen is added, the magnet attracts the oxygen and the balance swings to realign itself with the new field. Light reflected from a small mirror then can be used to indicate that degree of swing and hence, the oxygen concentration.

Water and particulate matter have to be removed before the sample enters this monitoring systems. It should be noted that NO and NO_2 are also paramagnetic and may cause some interference in the monitoring method if high concentrations are present.

Tables 5-11, 5-12, and 5-13 summarize information on extractives and in-situ monitoring instrumentations, including range capabilities, approximate cost, and ability to measure specific effluent gas components.

5.10 MANUAL STACK SAMPLING AND ANALYSIS APPROACHES

Incinerators burning hazardous waste are required to achieve a destruction and removal efficiency (DRE) of 99.99% for each principal organic hazardous constituent (POHC) in the waste feed as required under RCRA, as well as meeting emissions limitations for HCl and particulate matter. These pollutants are sampled and analyzed by manual extractive techniques at the exhaust stack.

Stack gas sample volume, stack moisture content, stack gas volume flow rate, and particulate emissions are typically determined by EPA Methods 2, 4, and 5 or, alternatively, ASTM Method D2928. Hydrochloric acid emissions are determined by midget impinger collection and subsequent titration. Stack emissions of POHC's may be determined using a modified EPA Method 5 apparatus and includes collection and analysis of particulate matter, gas phase organics and water present in the stack gas, with subsequent analysis done typically on a gas chromatograph/mass spectrometer (GC/MS) system. The following discussions describe in more detail each of these manual stack sampling approaches.

TABLE 5-11. EXTRACTIVE MONITOR SUMMARY[a]

Instrument vendor	Gases measured						Measurement range	Approximate cost in thousands of dollars
	SO_2	NO	NO_2	CO_2	CO	O_2		
Nondispersive infrared instruments								
Beckman	X	X		X	X		Various ranges in ppm or %	3 - 5.4
Bendix	X	X		X	X		0.5 ppm - 50%	3 - 4
Esterline Angus	X	X		X	X		2 ppm - 100%	5
Horiba	X	X	X	X	X		10 - 2,000 ppm	3 - 5
Infrared Ind.	X	X		X	X		200 ppm - 10%	1 - 2
Leeds and Northrop	X			X			0 - 1,000 ppm	5.5
MSA	X	X		X	X		0 - 2,000 ppm	3 - 4
Teledyne				X	X		0 - 1,000 ppm	11 - 13
Extract differential absorption instruments								
CEA	X	X			X		2 - 50,000 ppm	3 - 6
DuPont	X	X	X				1 ppm - 100%	13 - 23
Esterline Angus	X		X					
Teledyne	X						2 ppm - 100%	12 - 14
Western	X	X	X		X		75 - 5,000 ppm	12 - 22
Polarographic instruments								
Beckman						X	0 - 25%	1 - 1.5
IBC/Berkeley	X	X	X				0 - 1,000 ppm	2 - 5.5
Dynasciences	X	X	X		X	X	0.01 - 200,000 ppm	2 - 8
Interscan Corp.	X		X		X			1
Teledyne						X	0 - 25%	1.5
Theta Sensors (MRI)	X		X			X	1 - 20,000 ppm	1 - 4
Western Precipitator (Joy)	X		X	X	X	X	0 - 1,000 ppm	1.5
Electrocatalytic instruments								
CEA						X	0 - 25%	
Dynatron						X	0 - 25%	
Lear Siegler						X	0 - 25%	4.5 - 5.8
MSA						X	0.1 - 20.8%	2
Teledyne						X	0 - 25%	1.5
Thermox						X	0 - 25%	2
Paramagnetic instruments								
Beckman						X	0 - 25%	
MSA						X	0 - 25%	3
CEA						X		
SCOTT						X	0 - 100%	1 - 1.5
Ledds and Northrop						X		
Taylor-Servomex						X	0 - 100%	1 - 1.5

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[a] This is a representative listing of known vendors. It is not intended to be a complete listing of all suppliers of such equipment.

TABLE 5-12. IN-SITU MONITOR SUMMARY[a]

Vendor	Gases measured					Method			Measurement range	Approximate cost in thousands of dollars
	SO_2	NO	CO_2	CO	O_2	Opacity	In-stack	Cross-stack		
CEA					X		X			
Contraves Goerz	X	X	X	X				X		30
Dynatron					X		X		0 - 25%	
Environmental Data Corp.	X	X	X	X		X		X	0 - 5,000 ppm	20 - 40
Lear Siegler	X	X			X		X		0 - 500; 0 - 1,000; 0 - 1,500 ppm	4.5 - 17
Westinghouse					X		X			

[a] This is a representative listing of known vendors. It is not intended to be a complete listing of all suppliers of such equipment.

TABLE 5-13. OXYGEN ANALYZER SUMMARY[a]

Vendor	Analysis method			Sampling type	
	Paramagnetic	Polarographic	Electro-catalytic	In-Situ	Extractive
Astro			X	X	X
Beckman		X			X
Cleveland Controls	X		X	X	X
Corning			X	X	
Dynasciences		X			X
Dynatron			X	X	
Esterline Angus	X				X
Gas Tech		X			X
Hays-Republic			X	X	X
Joy		X			X
Lear Siegler			X	X	
Leeds and Northrop	X				X
Lynn		X			X
MSA	X		X		X
Scott	X				X
Taylor-Servomex	X				X
Teledyne		X			X
Thermox			X		X
Theta Sensors		X			X
Westinghouse			X	X	

[a] This is a representative listing of known vendors. It is not intended to be a complete listing of all suppliers of such equipment.

5.10.1 Hydrochloric Acid Emissions

The sampling procedure developed for the determination of hydrogen chloride emissions from stationary sources is basically a modification of the standard procedure for SO_2 determination (EPA Reference Method 6): The HCl method utilizes the same sampling equipment (i.e., probe, glassware, pump, dry gas meter, etc.) with the exception that a regular midget impinger is used for the first impinger in place of the midget bubbler used in Method 6. Dilute NaOH is used as the absorbing solution for HCl. After pretreatment of the impinger catches to remove possible interfering species, samples are analyzed for chloride ion by titration with a standard solution of mercuric nitrate [$Hg(NO_3)_2$].

A heated glass lined probe is used with the temperature maintained at 300 F or at stack temperature, whichever is greater. A pyrex wool plug is inserted in the inlet end of the probe in the same manner as required by Method 6. The impinger train, illustrated in Figure 5-45, which should be immersed in an ice bath during the sampling, consists of four midget impingers connected by glass U tubes and clamps. Impinger Nos. 1 and 2 should contain 15 mL of the absorbing solution (0.1N NaOH). Impinger No. 3 should contain 15 mL of 3% H_2O_2 solution, which will remove SO_2 from the sample stream. Impinger No. 4 is a dry impinger which functions to remove moisture from the sample stream. The impinger train is interfaced with the probe by using a short, right angle bend glass adaptor with the appropriate standard taper ground glass joints at either end. A standard Method 6 control box with umbilical cord is used to complete the sample train. A sampling rate of 2.0 liters per min is recommended with a total sample volume of 2.0 to 10.0 scf per sample, depending on the expected concentrations of HCl to be measured.

The Mercuric Nitrate Method involves titration of Cl^- with standard $Hg(NO_3)_2$ solution using bromophenol blue diphenylcarbazone mixed indicator. Diphenylcarbazone forms an intensely violet colored complex with the first slight excess of Hg^{++} beyond the equivalence point. The bromophenol blue performs two functions, the first being that it allows for a very accurate adjustment of the pH of the solution to be titrated to the range of 3.2 to 3.4 which is necessary for accurate results; and, secondly, its yellow color in the acid range serves as an excellent background color for detection of the violet colored complex formed at the endpoint.

Additional details on the sampling and analysis procedures can be found by consulting the Guidance Manual for Evaluating Permit Applications for the Operation of Incinerator Units.

5.10.2 Principal Organic Hazardous Constituents (POHC)

The sampling system used to obtain gaseous emission samples from the stack gas will be a modified version of that normally employed to perform EPA Reference Method 5 procedures. The system will consist of a quartz-lined, water-cooled sampling probe, a cyclone (optional), a high efficiency glass or quartz fiber filter, an XAD-2 sorbent resin module to allow for the collection of volatile organic vapors, four impingers and a control module. The sorbent module will be located between the filter assembly and the impinger train. A diagram of the sampling system is shown in Figure 5-46, and the sorbent module

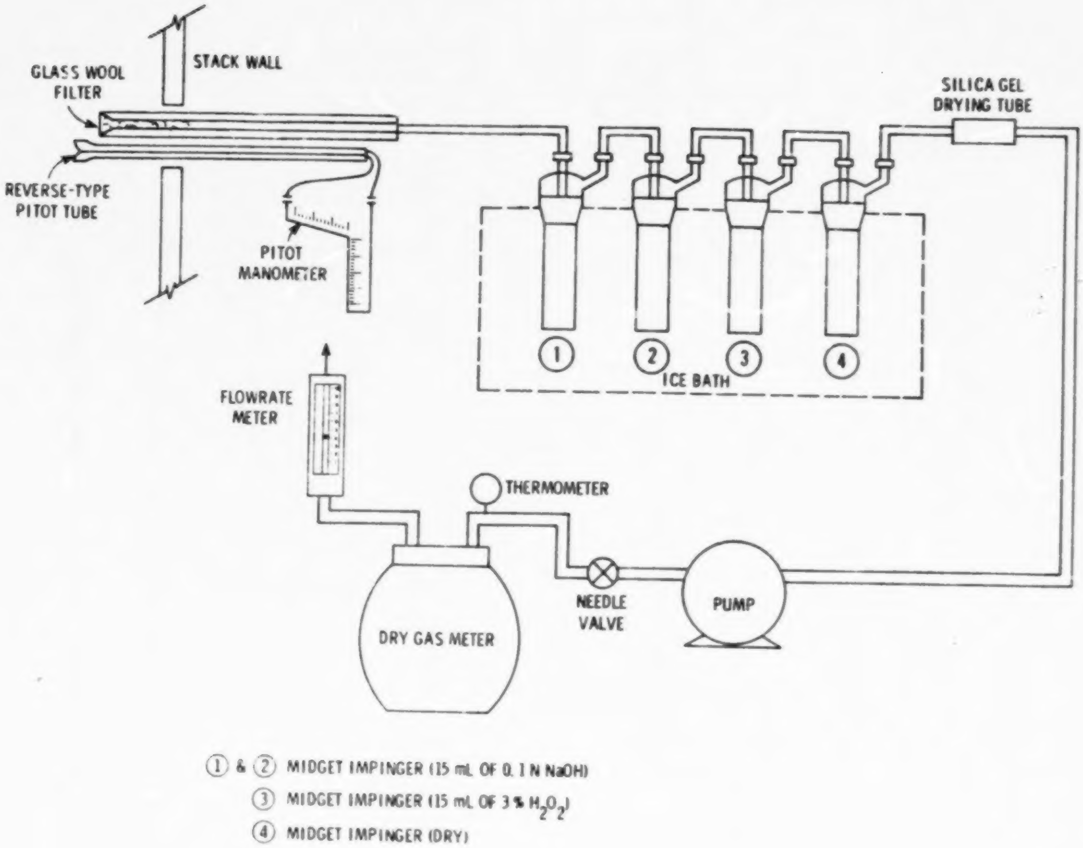
GLASS WOOL FILTER
STACK WALL
SILICA GEL DRYING TUBE
REVERSE-TYPE PITOT TUBE
PITOT MANOMETER
①
②
③
④
ICE BATH
FLOWRATE METER
THERMOMETER
NEEDLE VALVE
PUMP
DRY GAS METER
① & ② MIDGET IMPINGER (15 mL OF 0.1 N NaOH)
③ MIDGET IMPINGER (15 mL OF 3% H2O2)
④ MIDGET IMPINGER (DRY)

Figure 5-45. Schematic diagram of hydrogen chloride sampling train.

is shown in Figure 5-47. Sampling probe cooling is required to prevent severe probe damage that would occur if an unjacketed probe was placed in a zone where temperatures exceed 600°C (1100°F). Furthermore, the water cooling also assists in cooling the sample gas stream so that existing probe gas temperatures may be regulated to 205°C (400°F) as the gas passes through the filter. A schematic of the water cooled probe assembly is shown in Figure 5-48. The probe is constructed of stainless steel with a quartz liner. If the stack gas temperature is low, then a probe which meets the requirements of EPA Method 5 sampling may be used instead.

The ball or spherical joint of the probe connects to a glass cyclone with a collection flask attached. The use of the glass cyclone is optional. The purpose of the cyclone is to remove large quantities of particulates to prevent plugging of the filter. In gas streams where the particulate loading is expected to be light, the cyclone may be replaced with a glass tube connecting the probe to a glass filter holder. If used, the cyclone outlet is connected to the glass filter holder. The cyclone, flask, and filter holder are contained in an

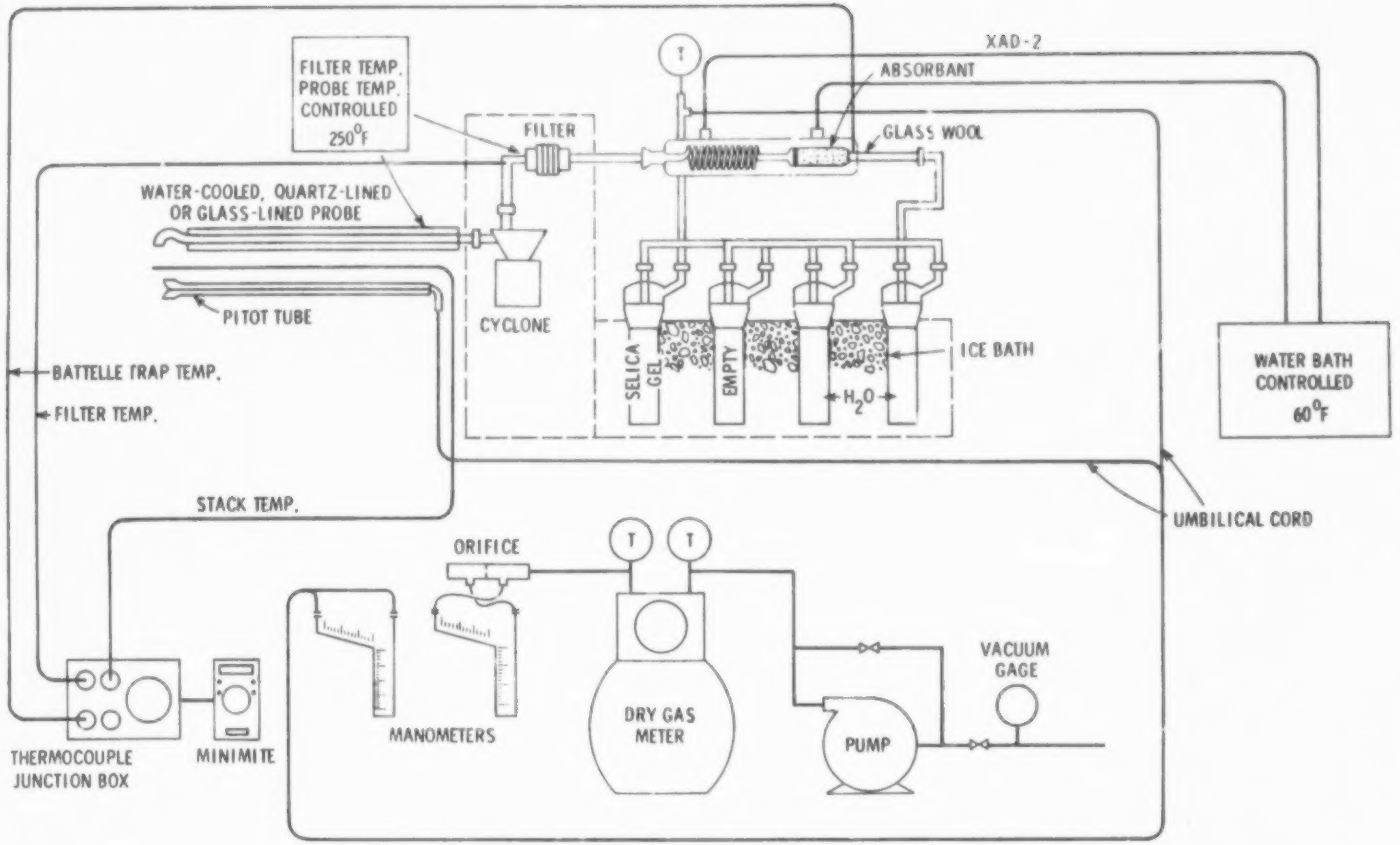
FILTER TEMP.
PROBE TEMP.
CONTROLLED
250°F
FILTER
T
XAD-2
ABSORBANT
GLASS WOOL
WATER-COOLED, QUARTZ-LINED
OR GLASS-LINED PROBE
PITOT TUBE
CYCLONE
SELICA GEL
EMPTY
H2O
ICE BATH
WATER BATH
CONTROLLED
60°F
BATTELLE TRAP TEMP.
FILTER TEMP.
STACK TEMP.
UMBILICAL CORD
ORIFICE
T
T
VACUUM
GAGE
DRY GAS
METER
PUMP
MANOMETERS
THERMOCOUPLE
JUNCTION BOX
MINIMITE

Figure 5-46. Modified EPA Method 5 sample train for POHC collection.

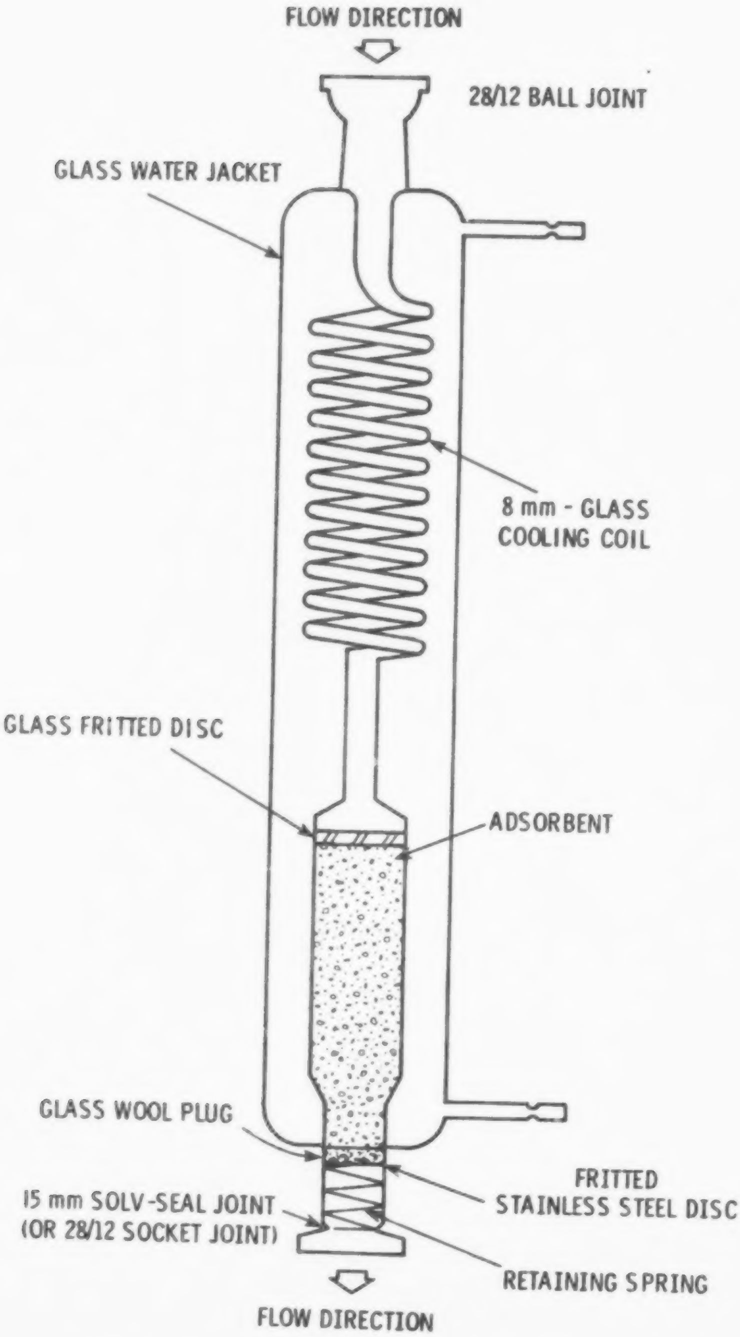
FLOW DIRECTION
28/12 BALL JOINT
GLASS WATER JACKET
8 mm - GLASS
COOLING COIL
GLASS FRITTED DISC
ADSORBENT
GLASS WOOL PLUG
FRITTED
STAINLESS STEEL DISC
15 mm SOLV-SEAL JOINT
(OR 28/12 SOCKET JOINT)
RETAINING SPRING
FLOW DIRECTION

Figure 5-47. Adsorbent sampling system.

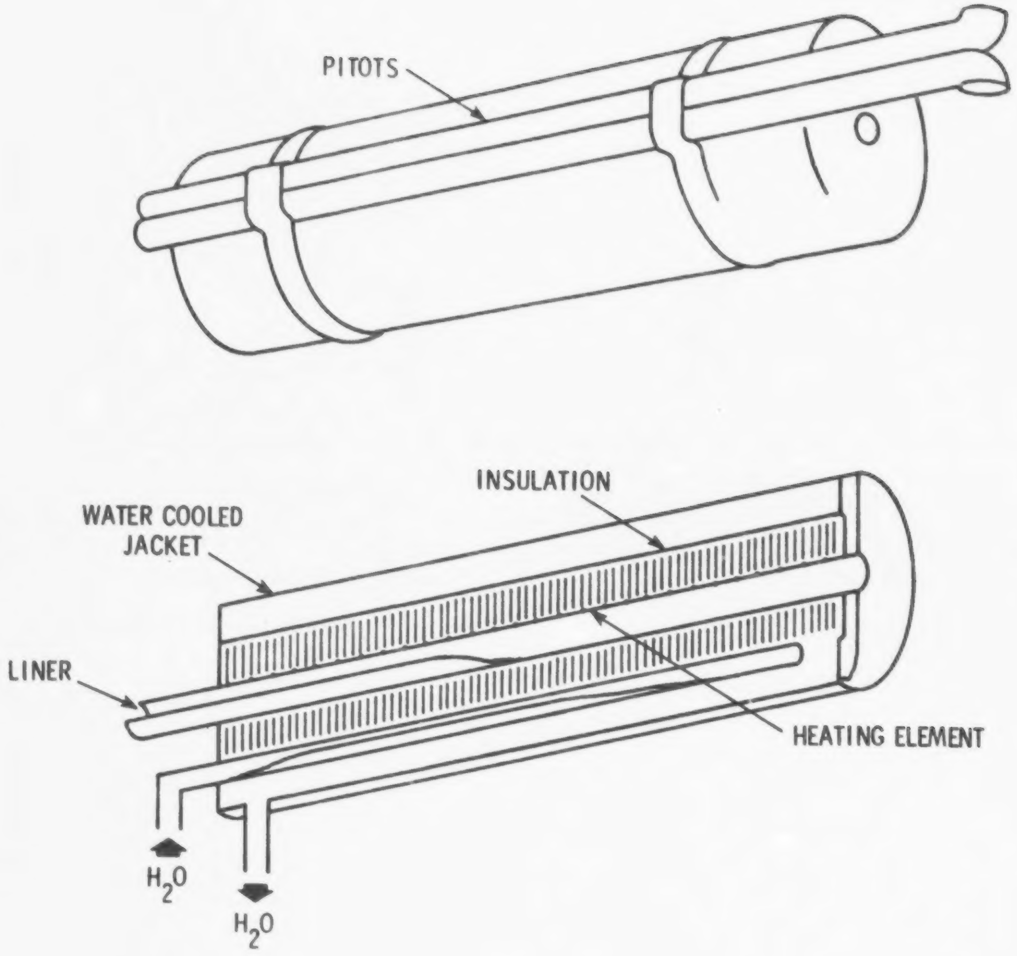
PITOTS
WATER COOLED JACKET
INSULATION
LINER
HEATING ELEMENT
H_2O
H_2O

Figure 5-48. Temperature controlled cooled probe.

electrically heated enclosed box, which is thermostatically maintained at a temperature of [120°C ± 12°C (250°F ± 25°F)] which is sufficient to prevent water condensation in the portion of the train contained in this box.

Downstream of the heated filter, the sampled gas passes through a module that is filled with roughly 20 gms of XAD-2 resin. The XAD-2 sorbent is a porous polymer resin with the capability of absorbing a broad range of organic species. Before reaching the sorbent resin, the sampled gas should be cooled to a temperature of 15°C (60°F). This cooling operation may cause some of the water vapor contained within the sampled stream to condense, which, in turn, may result in some of the organic vapor becoming entrained in the condensate. For this reason, the condensate must be allowed to percolate through the resin bed prior to it being discharged into the impinger located below the sorbent module.

At the downstream side of the sorbent module, four impingers are connected in series and immersed in an ice bath. The first impinger, connected to the outlet of the sorbent module, is of the Greenberg-Smith design, modified by replacing the tip with a 0.3 cm (0.5 in.) inside diameter glass tube extending to within 1.3 cm of the bottom of the flask. This impinger is initially filled with 100 mL of scrubbing solution. The selection of scrubbing solution is contingent upon the type of inorganic vapors that are suspected of being contained in the stack gas. A caustic solution such as sodium hydroxide or sodium acetate is used to collect acid gases such as HCl. (The sodium acetate is used to prevent depletion of scrubbing reagent by carbon dioxide.) For collection of volatile metals (mercury, arsenic, selenium) a strongly oxidizing solution (such as silver catalyzed ammonium persulfate) must be used. The second and third impinger are Greenberg-Smith types modified like the first. They may be filled with an organic liquid with a high boiling point, such as isooctane, in order to trap organics not adsorbed on the resin. The fourth impinger is also a modified Greenberg-Smith and contains approximately 175 grams of accurately weighed silica gel. If volatile metals collection is not desired, then the impinger section may set up as an EPA Method 5 backhalf, as shown in Figure 5-46.

In connecting the sampling train together, no stopcock grease should be used on any joint upstream of the sorbent module as it may flow into the sampled stream and contaminate the particulate and organic vapor portion of the sample. This requirement means that some extra effort is required to achieve a leak check. Nevertheless, it is essential to avoid stopcock grease since its presence would make organic analysis virtually impossible.

Alternatively, a source assessment sampling system (SASS) train may be used for stack gas sampling when a large sample is required and the stack gas temperature is less than 500°F. The SASS train operates at a 5 cfm flow rate and collects a 25.5 m^3 sample in a three-hour period. The SASS train consists of a stainless steel probe that connects to three cyclones and a filter in an oven module, a gas treatment section, and an impinger series, as shown in Figure 5-49. Size fractionation is accomplished in the cyclone portion of the SASS train, which incorporates the three cyclones in series to provide large collection capacities for particulate matter nominally size-classified into three ranges: (a) 10 μm, (b) 3 μm to 10 μm, and (c) 1 μm to 3 μm. By means of a standard 142-mm or 230-mm filter, a fourth cut, <1 μm, is also obtained. The gas treatment system

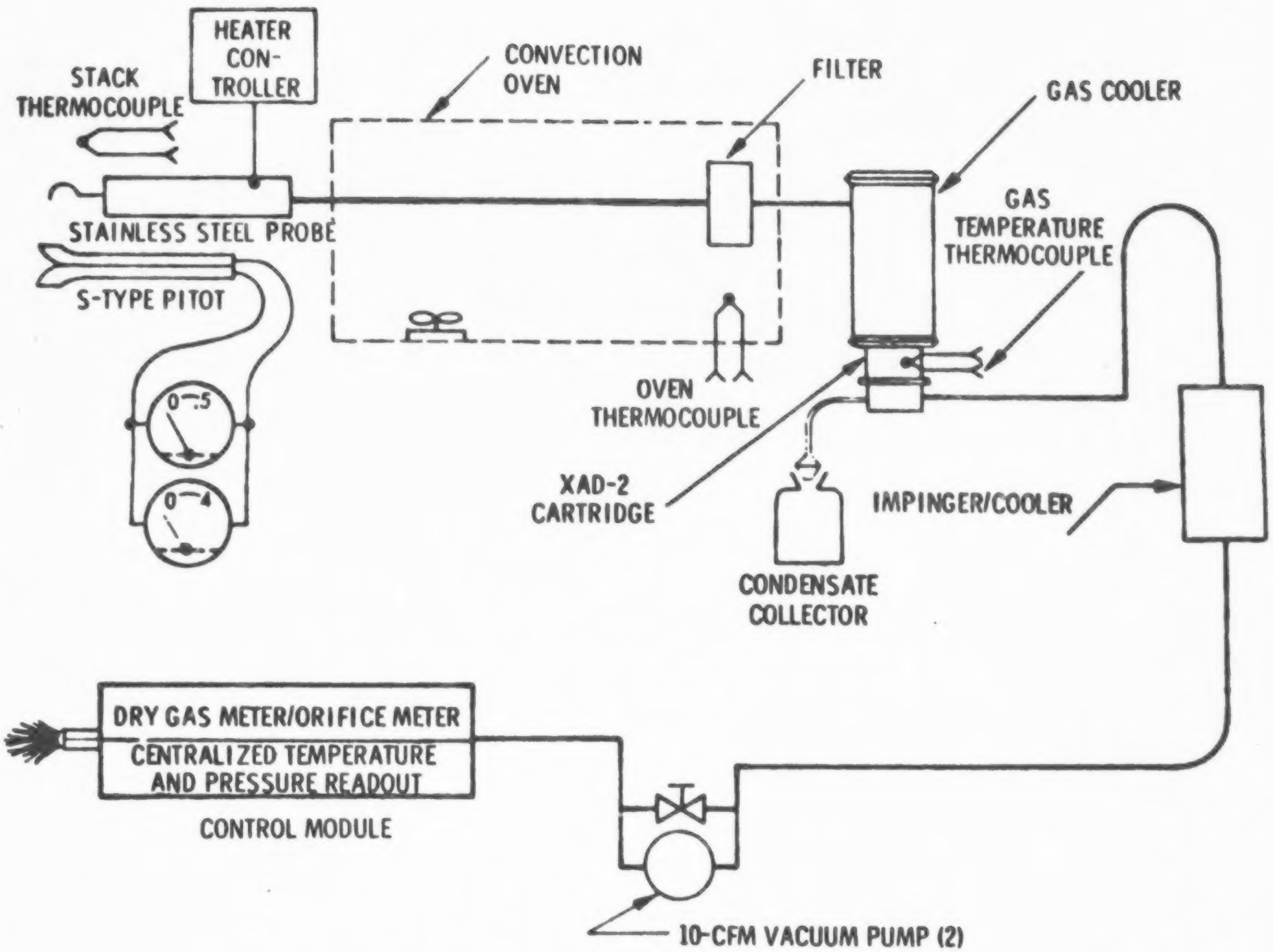
STACK THERMOCOUPLE
HEATER CON-TROLLER
CONVECTION OVEN
FILTER
GAS COOLER
STAINLESS STEEL PROBE
GAS TEMPERATURE THERMOCOUPLE
S-TYPE PITOT
0–.5
0–4
OVEN THERMOCOUPLE
XAD-2 CARTRIDGE
IMPINGER/COOLER
CONDENSATE COLLECTOR
DRY GAS METER/ORIFICE METER
CENTRALIZED TEMPERATURE AND PRESSURE READOUT
CONTROL MODULE
10-CFM VACUUM PUMP (2)

Figure 5-49. SASS schematic.

follows the oven unit and is composed of four primary components: the gas cooler, the sorbent trap, the aqueous condensate collector, and a temperature controller. Volatile organic material is collected in a cartridge or "trap" containing sorbent, which is designated to be XAD-2, a microreticular resin with the capability of absorbing a broad range of organic species. Volatile inorganic elements are collected in a series of impingers that follow the condenser and sorbent system. The last impinger in the series contains silica gel for moisture removal. Trapping of some inorganic species also may occur in the sorbent module. The pumping capacity is supplied by two 10-ft^3/min, high-volume vacuum pumps, while required pressure, temperature, power, and flow conditions are regulated through a main controller. At least 60 A of power at 100 V is needed for operating the sampling equipment.

The organic "trap" packings may be extracted using a Soxhlet extractor. This extract and organic liquids in the impingers may be analyzed for POHCs using the methods in "Test Methods for Evaluating Solid Wastes," EPA SW-846, 1980. Methods presented in EPA SW-846 may be used to analyze scrubber water and ash samples as necessary to compute a mass balance on POCH's. In addition, particulates collected on the filters and cyclones must be extracted and analyzed in order to compute the mass balance. A full mass balance on the POHC's in the waste require monitoring at the following locations:

- Stack gas
- Particulates collected from the stack gas
- Ash
- Scrubber liquid
- Other residues
- Waste feed composition

5.10.3 Calculation of Sample Volume Required to Show 99.99% DRE

Incinerators burning hazardous waste must achieve a destruction and removal efficiency (DRE) of 99.99% for each principal organic hazardous constituent (POHC) in the waste feed. The DRE is determined from the following equation:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} \times 100$$

where W_{in} = Mass feed rate of the principal organic hazardous constituent (POHC) in the waste stream feeding the incinerator, lb/hr

W_{out} = Mass emission rate of the principal organic hazardous constituent (POHC) present in exhaust emissions prior to release to the atmosphere, lb/hr

W_{in} is calculated using the following formula:

$$W_{in} = \text{(Concentration of POHC in waste)(Waste feed rate)}$$

POHC concentrations must be expressed in percentages when applying this formula. The waste feed rate is expressed in mass per unit time and must be consistent with the units used to express W_{out}. If a waste is co-fired with auxiliary fuel, the auxiliary fuel feed rate does not affect the calculation of W_{in}.

W_{out} is calculated from stack sampling data and involves three steps:

- Computation of stack gas sample volume
- Computation of POHC concentration in stack sample
- Computation of stack gas volume flow rate

Stack gas sample volume and stack gas volume flow rate may be determined by EPA Methods 2 and 5 or ASTM Method D2928. Stack emissions of POHCs may be determined using a modified EPA Method 5 apparatus and includes collection and analysis of particulate matter, gas phase organics and water present in the stack gas.

The following sample calculation will identify the minimum volume necessary to demonstrate a 99.99% DRE:

Step 1 - Computation of maximum W_{out} to satisfy 99.99% DRE

Given: POHC designated by the permit writer: hexachlorobenzene

Concentration of POHC in waste feed: 1.0%

Waste Feed Rate: 1,000 lbs/hr

$$\begin{aligned} W_{in} &= \text{(Concentration of POHC in waste)(Waste feed rate)} \\ &= (0.01)(1{,}000 \text{ lb/hr}) \\ &= 10 \text{ lb/hr} \end{aligned}$$

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} \times 100$$

$$\begin{aligned} W_{out} &= W_{in}\ (1\text{-DRE}) \\ &= (10 \text{ lb/hr})(1-0.9999) \\ &= 0.001 \text{ lb/hr} \end{aligned}$$

Note: The expression of the DRE to 5 or 6 decimal places is justified because an error by as much as 25% in the W_{out} would affect only the fifth decimal place.

Step 2 - Computation of minimum weight of POHC sample that can be collected

Given: Detection limit of hexachlorobenzene in analytical sample extract as injected in the GC/MS: 1 ng/µL, or 1 µg/mL [35].

Average Extraction Efficiency: 60%

Because the extracted sample is concentrated via evaporation before injection into the GC/MS, then the minimum weight of collected hexachlorobenzene is independent of extract liquid volume.

The minimum detectable total weight of POHC collected as obtained from laboratory analysis

$$
\begin{aligned}
W_{sample} &= \text{(Detection limit)/(Extraction efficiency)} \\
&= (1\ \mu L/mL)/(0.60) \\
&= 1.667\ \mu g
\end{aligned}
$$

Step 3 - Computation of the POHC stack gas loading

Given: Stack gas volume flow rate at standard conditions, Q: 85,382 scf/min

$$Cg = \frac{\text{Total weight of POHC in sample}}{\text{Volume of sample at standard conditions}}$$

$$
\begin{aligned}
Cg &= \frac{W_{out}}{Q} \times \frac{hr}{60\ min} \\
&= \frac{0.001\ lb/hr}{85{,}382\ scf/min} \times \frac{hr}{60\ min} \\
&= 1.95 \times 10^{-10}\ lb/scf = 8.85 \times 10^{-7}\ grams/scf
\end{aligned}
$$

Note: This computation assumes 100% collection of the POHC on the filter, resin module, and impingers.

Step 4 - Computation of minimum stack gas sample volume

$$
\begin{aligned}
V_{m(std)} &= \frac{W_{sample}}{Cg} \\
&= \frac{1.667 \times 10^{-6}\ grams}{8.85 \times 10^{-7}\ grams/scf} \\
&= 1.884\ scf
\end{aligned}
$$

5.11 PLANT CONDITION MONITORING SYSTEMS

The presence of defects in machinery and mechanical structures can lead to catastrophic failure. Plant facilities which are super-designed for safety and minimal downtime (e.g., nuclear power plants and oil refineries) utilize large fixed-base condition monitoring systems for lowered repair costs, lower production losses, and decreased accident and fire risks.

Defects present are characterized by corresponding abnormalities and changes in acoustic and vibratory emission patterns. By the use of sensors small defects in bearings and gears, growing cracks in shafts and weld joints, loose parts, and operating deficiencies such as pump cavitation can be detected early enough to either allow correction of the problem or provide time for predictive maintenance planning. These plant-wide incipient failure detection (IFD) systems can sequentially examine more than 800 channels and quantize their vibratory or acoustic energy levels. The signal is compared with the previously obtained energy level retrieved from the memory bank of a dedicated minicomputer. Significant deviations are programmed to cause an alarm annunciation [36].

5.11.1 Machine Vibratory Signature Analysis

Traditional machinery vibration signature analysis (MVSA) is a method of determining the mechanical condition of an operating machine by monitoring and analyzing frequency characteristics produced by internal elements using narrow band spectrum analysis techniques.

Vibration signature analysis makes use of the fact that vibration produced by a machine contains a great number of discrete frequencies, some of which can be tied directly to the operating dynamics of particular elements within the machine. When the amplitude of a specific frequency or pattern of frequencies changes, it represents a change within the machine and possibly a deteriorating condition.

Vibration measuring equipment is often used to detect solids build-up on fan blades, e.g., ID fans. If the vibration exceeds a preset level, the fans are shutdown, clean and repaired, if necessary [15].

5.11.2 High Frequency Acoustic Emission Analysis

The basic premise of high frequency acoustic IFD monitoring is that the presence of defects in machinery and mechanical structures is characterized by corresponding abnormalities and changes in the acoustic signature and that machinery vibration is inevitably accompanied or even preceded by metal deformation. Metal deformation generates "acoustic emissions," i.e., noise resulting from the propagation of intergranular dislocations in material subjected to stress.

For early identification of failure these defects must be detected when they first develop and are quite small. However, the amount of detectable energy released from a small defect is usually negligible in comparison to normal machinery operating noise. Fortunately, operating noise tends to be concentrated in the low frequency range of vibration while defect-originated energy extends to much higher frequencies. It is this frequency separation that accounts for the success of IFD technology.

High frequency acoustic techniques have been shown to be more effective in detecting mechanical failures at a very early stage then the popularly used low frequency vibration and sound techniques. Furthermore, high frequency acoustics have very often picked up fluid flow deviations such as pump cavitation and mechanical seal leakage.

5.12 SCRUBBER/QUENCH WATER AND ASH HANDLING

5.12.1 Description of Potential Incinerator Wastes

Operation of a hazardous waste incinerator typically produces a number of secondary products, namely quench water, scrubber effluent, and ash. The following subsections describe each of these possible secondary wastes and provide information on their potential composition.

5.12.1.1 Quench Water--
Following the afterburner section, a quench section is usually installed to reduce the combustion gas temperature prior to entering the scrubber. Entering temperatures are approximately 1,800°F to 2,000°F and the exit temperature may be below 250°F. The inclusion of the quench section becomes necessary when nonmetallic materials are used for scrubber construction and packing. The upper temperature limit for sustained operation is about 300°F for polyester and epoxy fiberglass and 150°F for PVC [37]. The gases are commonly quenched with a water spray at a rate capable of reducing the gas temperature to a desired level. Besides lowering the flue gas temperature, this quench water functions as a scrubber by removing some particulate matter and certain gaseous pollutants from the exhaust stream.

Four basic designs are used to generate the water spray in quench towers:

> (1) Air and water nozzle (2) High pressure sequenced spray nozzles (3) Orifice plate (4) Low pressure venturi or variable throat venturi

The type of device used depends upon the composition of the quench water, the composition of the exhaust gas, the type of air pollution control equipment being used, the initial investment, and maintenance considerations. Various quenching devices are illustrated in Figure 5-50.

The air and water nozzle system is the most sophisticated device and requires a fresh water feed, free from particles which might clog the spray nozzles. It also requires the least amount of water because it produces small, uniform droplets which efficiently cover an exhaust area.

High pressure sequenced spray nozzles operate on a demand basis. Initially, certain banks of spray are activated and as the gas temperature rises, additional banks come on to maintain a constant temperature. This system, like the air and water nozzle system, cannot operate on clarified recycle water due to dissolved and suspended solids; however, where fabric filters or electrostatic precipitators follow, these types of systems are necessary to prevent damage to these units from excessive heat.

An orifice plate is an effective precleaner capable of removing particulates down to 5-10 microns [38]. It is simply a perforated plate through which water is forced. It is very effective preceding a high energy scrubber because it removes the larger particles which would create an erosion problem in the high velocity throat.

Another device which is essentially maintenance free and works well when used ahead of a scrubber is a low pressure venturi. Water nozzles, located just upstream of the venturi throat, saturate the flow and knock out the larger particles. In a variable throat venturi, gas velocities and corresponding pressure drop can be varied by adjusting throat diameter. For any particle size, the collection efficiency increases with increased energy consumption. Increased energy can be obtained by increasing gas velocities through the

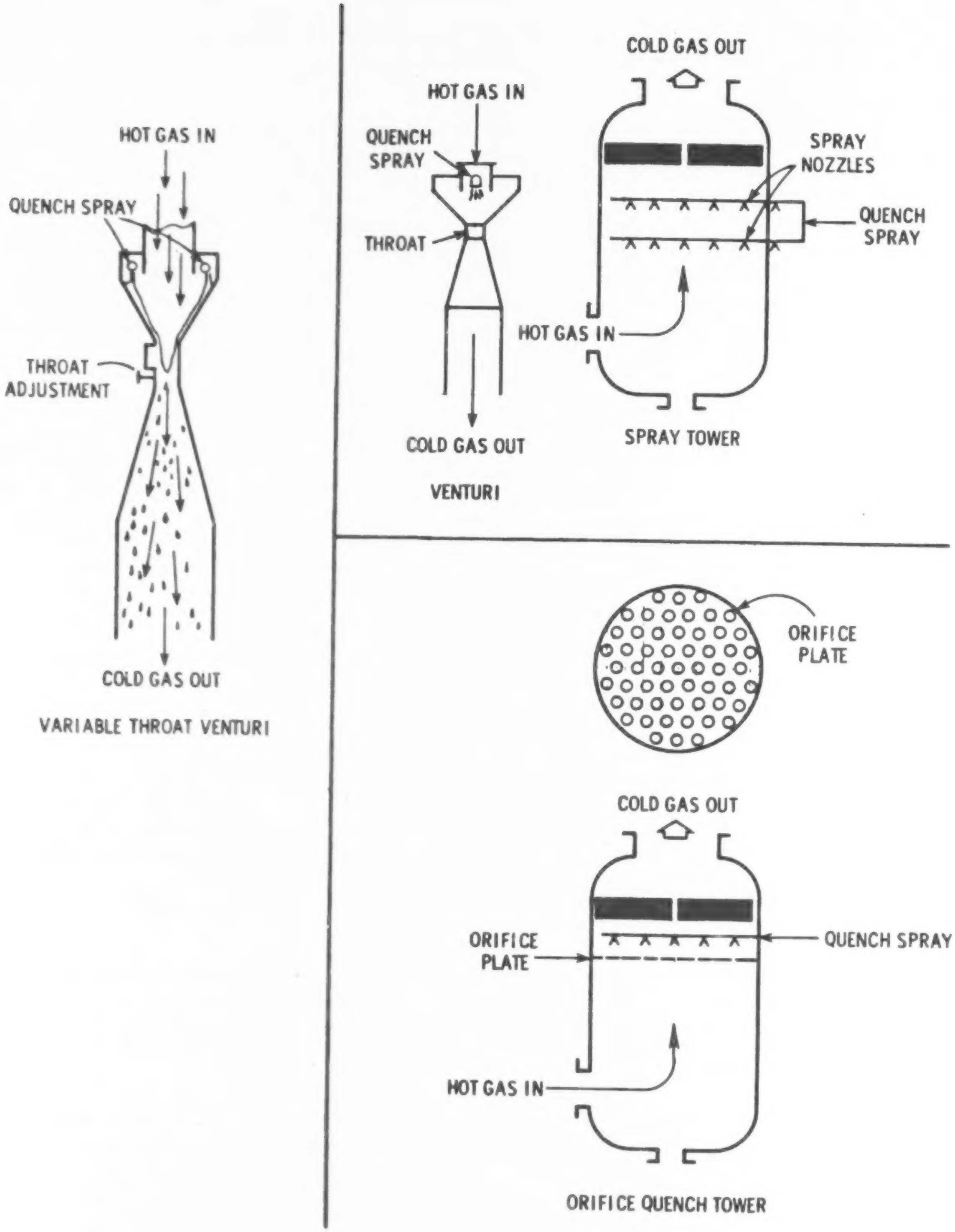
HOT GAS IN
QUENCH SPRAY
THROAT ADJUSTMENT
COLD GAS OUT
VARIABLE THROAT VENTURI
HOT GAS IN
QUENCH SPRAY
THROAT
COLD GAS OUT
VENTURI
COLD GAS OUT
SPRAY NOZZLES
QUENCH SPRAY
HOT GAS IN
SPRAY TOWER
ORIFICE PLATE
COLD GAS OUT
ORIFICE PLATE
QUENCH SPRAY
HOT GAS IN
ORIFICE QUENCH TOWER

Figure 5-50. Various quenching devices [38].

variable throat. Due to their larger and less restrictive water nozzle systems, both the orifice plate and low pressure venturi or variable throat venturi quenching devices may be operated using recycled quench water, after passing through a reduction and clarification process.

A generalized schematic of incinerator facilities and schematic of a rotary kiln facility with quench spray chamber and venturi scrubber are illustrated in Figures 5-51 and 5-52, respectively.

Material selection of the nozzles is very important because the cooling effect of the spray nozzle can cause condensation of the hot acidic gases along the wall of the spray nozzle, and these gases will react with the metal at or below the dewpoint of the acid. Also, the water will immediately react with the acid gas to form, for example, hydrochloric acid mist in the fine spray droplets, if an organochlorine waste is being destroyed. These are recycled and result in direct contact with the nozzle body.

The main body of the quench chamber is in contact with the highly acidic solution formed by the partial scrubbing of the combustion gases. Material selection is also important for this section. Hastelloy alloy B is a material generally recommended for the quench section, spray nozzles, and the duct work leading into the quench chamber. This material is a nickel-molybdenum alloy developed primarily for resistance to the corrosive effects of hydrochloric acid. This alloy also possesses useful high-temperature properties. In oxidizing atmospheres, the alloy may be used at temperatures up to 1,400°F. In reducing atmospheres, the alloy may be used at substantially higher temperatures.

Hastelloy alloy B is particularly well suited for equipment handling hydrochloric acid at all concentrations and temperatures including the boiling points. Hastelloy alloy B is easily fabricated, and can be forged and cold-formed by a variety of methods. Most of the common welding methods can be used to weld it, although the oxy-acetylene process is not recommended when the alloy is to be used in corrosion service.

Inconel alloy 625 and Incoloy alloy 825 are two other materials which show good resistance to hydrochloric acid and could thus be used in the quench section.

The composition of the quench water depends directly on the wastes being incinerated. Table 5-14 summarizes the possible air pollutants that may be produced and captured by the quench tower and by other air pollution control devices. Because chlorinated organic compounds constitute the most common type of hazardous waste disposed of by incineration, quench waters are generally acidic and must be neutralized before discharge. Although hazardous species would not typically be present in quench water, this is typically verified before the effluent is disposed. Quench water is normally combined with the scrubber effluent for treatment and disposal.

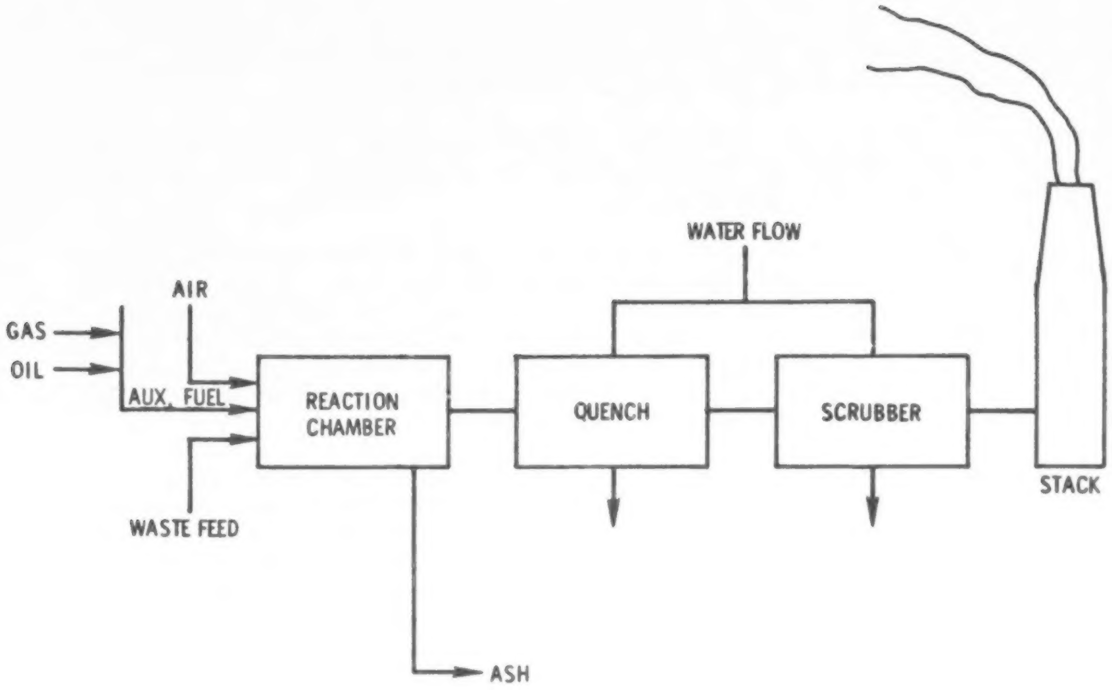
WATER FLOW
AIR
GAS
OIL
AUX. FUEL
REACTION CHAMBER
QUENCH
SCRUBBER
STACK
WASTE FEED
ASH

Figure 5-51. Generalized schematic of incinerator facility.

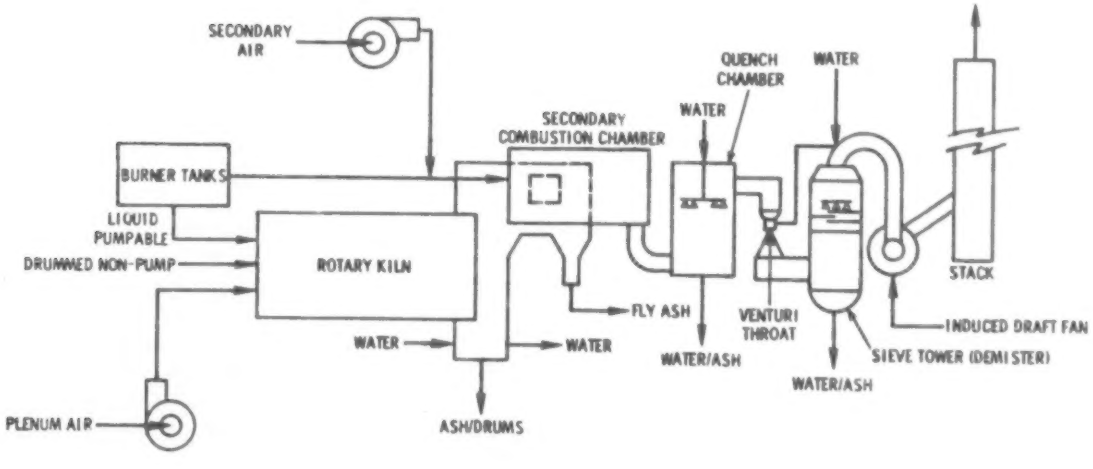
SECONDARY AIR
QUENCH CHAMBER
WATER
SECONDARY COMBUSTION CHAMBER
WATER
BURNER TANKS
LIQUID PUMPABLE
DRUMMED NON-PUMP
ROTARY KILN
FLY ASH
VENTURI THROAT
STACK
INDUCED DRAFT FAN
SIEVE TOWER (DEMISTER)
WATER
WATER
WATER/ASH
WATER/ASH
ASH/DRUMS
PLENUM AIR

Figure 5-52. Schematic of rotary kiln facility with quench spray chamber and venturi scrubber.

TABLE 5-14. POTENTIAL AIR POLLUTANTS FROM HAZARDOUS WASTE INCINERATION

		Likely removal sites		
Hazardous waste	Air pollutants[a]	Quench tower	Scrubber	Baghouse or ESP
Organic materials containing:				
1. C, H, O only	Thermal NO_x[b]	-	c	-
2. Cl	HCl	X	X	-
3. Br	HBr	X	X	-
4. F	HF	X	X	-
5. S	SO_x	-	X[d]	-
6. P	P_2O_5	-	X[e]	-
7. N	NO_x	-	c	-
8. C, N	CH^- compounds	X	X	-
Materials containing some inorganic components:[f]				
1. Nontoxic minerals only, e.g., Al, Ca, Na	Particulate matter	X	X	X
2. Toxic elements including metals, eg., PB, As, Sb	Particulate matter	X	X	X
	Volatile species[g]	-	X[g]	X[g]

---

[a] Based on complete destruction (i.e., oxidation) of hazardous waste.

[b] NO_x produced from atmospheric nitrogen at high temperatures (about 1,100°C) in the incinerator.

[c] NO_x is not normally controlled. Special scrubbers have been developed for NO_x control in special circumstances.

[d] Alkaline scrubbers are required for efficient SO_x control.

[e] Special high efficiency scrubbers are needed to collect phosphoric acid mist.

[f] A portion of the inorganic components may be removed as bottom ash from the incinerator.

[g] Certain elements from volatile species (e.g., AS_2O_3) that condense out in the exhaust gas as the temperature falls. They can be collected in the gas phase by special scrubbers or as particulate matter at low temperatures by normal particulate control equipment.

5.12.1.2 Scrubber Effluents--

Characterization of scrubber effluents varies considerably from that of the quench water. Quench towers are primarily used to reduce the combustion gas temperatures prior to entering the scrubber, whereas scrubbers are primarily used to reduce noxious gases from the combustion gas prior to discharge to atmosphere. Commonly used scrubber types, design, material of construction, scrubber selection for specific applications, advantages, and disadvantages, etc., are covered in detail in Chapter 4.

In an incinerator burning chlorinated organic compounds, if water is the scrubbing fluid, the wastewater effluent will contain suspended particulates, dissolved HCl (i.e., hydrochloric acid), and other soluble constituents which may be present (e.g., trace quantities of organics and waste constituents that may be soluble). If alkaline scrubbing solutions are used, the HCl will undergo neutralization reactions to produce additional water and salts (either NaCl or $CaCl_2$ depending on whether NaOH or $Ca(OH)_2$ was used in the scrubbing solution). Because alkaline materials are often used in excess, residual amounts of these substances will be present. The wastewater will also contain suspended particulates and any soluble combustion products.

The venturi scrubbing process involves either a single pass of the scrubbing fluid or recirculation of the scrubbing fluid. If recirculation is used, scrubber fluid is recirculated through the venturi scrubber until the total dissolved solids (TDS) content reaches approximately 3% [39]. When this occurs, a portion of the scrubbing fluid is removed (blowdown) and new scrubbing fluid is added to make up for the fluid lost as blowdown. The blowdown from the single pass or recirculation scrubbing systems is neutralized (as needed) before delivery to on-site wastewater treatment processes, on-site storage facilities (e.g., evaporation ponds), or dispensing to the municipal sewer or a receiving water body. Single pass and recirculating scrubber systems are illustrated in Figure 5-53 and 5-54, respectively.

Alternative types of scrubber systems have been designed to recover HCl produced during organochlorine incineration. Such systems can produce commercial grade hydrochloric acid streams with concentrations ranging between 20% and 60% HCl [39]. These systems utilize aqueous solutions to absorb HCl from the combustion chamber effluent gas stream, and the resulting solution is concen trated via water extraction procedures. Residual HCl that may be left in the remaining combustion gas stream can be removed by passing this stream through an alkaline neutralization tower, or by using conventional gas scrubbing procedures.

Characteristics of Blowdown from Recirculating Scrubbers--Blowdown from recircu lation systems occurs when the salinity reaches approximately 3 percent. This relates to a TDS value of 30,000 milligrams per liter [39]. The blowdown rate is variable, depending on the amount of chlorine in the liquid incinerated and on the liquid feed rate.

Characteristics of Single-Pass Scrubber Effluent--The characteristics of single-pass scrubber effluents are highly variable, depending on the chlorine content of the liquid incinerated, the liquid feed rates, the scrubber solution feed rates, and the efficiency of the scrubber, Because single-pass systems have so many variables, it is not possible to obtain a normal or average TDS concentration. However, it is possible to estimate the magnitude of TDS concentration. This has been done by using two sets of data shown in Tables 5-15 and 5-16. The data were picked because their operating parameters produced two extremes in scrubber water quality, as shown in Table 5-15. Generally, scrubber wastewaters will contain TDS concentrations less than 40,000 milligrams per liter.

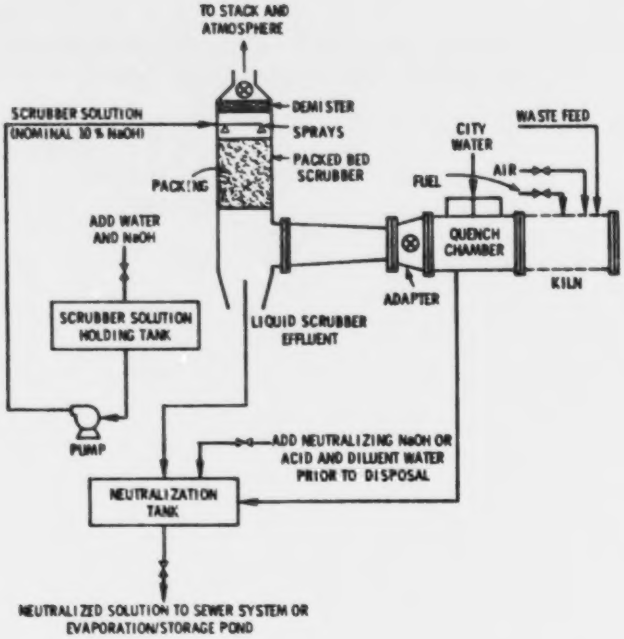
TO STACK AND ATMOSPHERE
DEMISTER
SCRUBBER SOLUTION (NOMINAL 10 % NaOH)
SPRAYS
PACKED BED SCRUBBER
PACKING
CITY WATER
WASTE FEED
AIR
FUEL
ADD WATER AND NaOH
QUENCH CHAMBER
ADAPTER
KILN
SCRUBBER SOLUTION HOLDING TANK
LIQUID SCRUBBER EFFLUENT
PUMP
ADD NEUTRALIZING NaOH OR ACID AND DILUENT WATER PRIOR TO DISPOSAL
NEUTRALIZATION TANK
NEUTRALIZED SOLUTION TO SEWER SYSTEM OR EVAPORATION/STORAGE POND

Figure 5-53. Single-pass scrubber system [37].

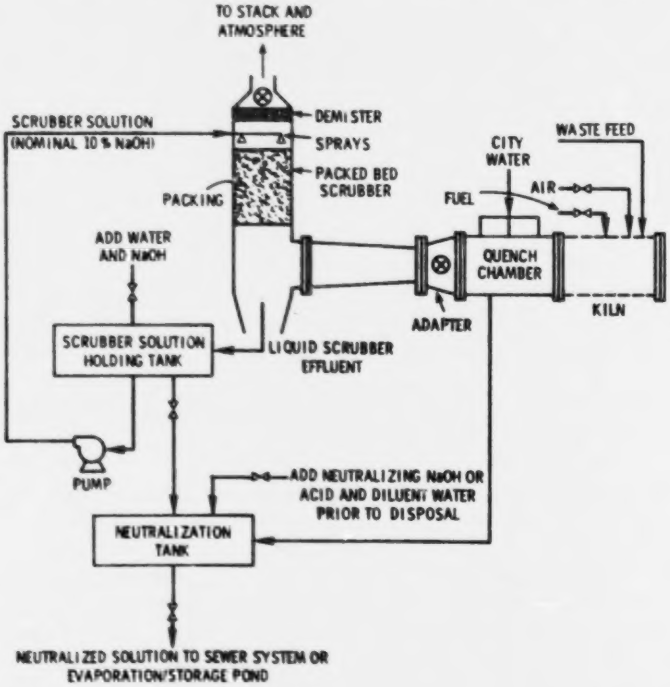
TO STACK AND ATMOSPHERE
DEMISTER
SCRUBBER SOLUTION (NOMINAL 10 % NaOH)
SPRAYS
PACKED BED SCRUBBER
PACKING
CITY WATER
WASTE FEED
AIR
FUEL
ADD WATER AND NaOH
QUENCH CHAMBER
ADAPTER
KILN
SCRUBBER SOLUTION HOLDING TANK
LIQUID SCRUBBER EFFLUENT
PUMP
ADD NEUTRALIZING NaOH OR ACID AND DILUENT WATER PRIOR TO DISPOSAL
NEUTRALIZATION TANK
NEUTRALIZED SOLUTION TO SEWER SYSTEM OR EVAPORATION/STORAGE POND

Figure 5-54. Recirculating scrubber system [37].

TABLE 5-15. SCRUBBER WATER AND WASTE PARAMETERS FOR TWO LAND-BASED LIQUID INJECTION INCINERATORS [39]

	Waste incinerated	
	Hexachlorocyclopentadiene[a]	Nitrochlorobenzene[b]
Fresh scrubber water feed rate (liters/min)	60	3,200
Caustic solution feed rate (liters/min)	23.8	8.5
Type of solution used	12% NaOH	32% $Ca(OH)_2$
Liquid waste feed rate (kg/hr)	52.8	1,893
Elemental chlorine content of the waste	77%	10%

[a] Source: Reference 34.

[b] Source: Reference 37.

TABLE 5-16. SCRUBBER WATER QUALITY [39]

	Waste incinerated	
	Hexachlorocyclopentadiene	Nitrochlorobenzene
Chlorides (mg/L)	11,000	1,300
Calcium (mg/L)	--	530
Sodium (mg/L)	25,670	--
Total dissolved solids (mg/L)	36,670	1,830

It can be expected that the HCl recovery processes will have much lower TDS concentrations than systems which do not recover HCl because a large proportion of the dissolved ions would be removed during recovery of the acid.

Scrubber effluents generally contain very little organic material due to high waste destruction efficiencies required.

The particular gaseous pollutant of interest may require scrubbing with a medium specific for the pollutant. Water is adequate for a gas such as HCl, but other scrubber media may be required for SO_2, NO_x, etc. In some cases, multiple stages are required to efficiently remove a combination of gaseous pollutants, with each stage specific for given pollutant. Two-stage and three-stage scrubber systems are illustrated in Figures 5-55 and 5-56, respectively. The type of technology illustrated in Figure 5-55 is not normally utilized for a hazardous waste incinerator. It is presented here for scrubber review. The three stage scrubber system illustrated in Figure 5-56 was implemented for a research project in an attempt to very carefully scrub effluent from a pesticide incineration program.

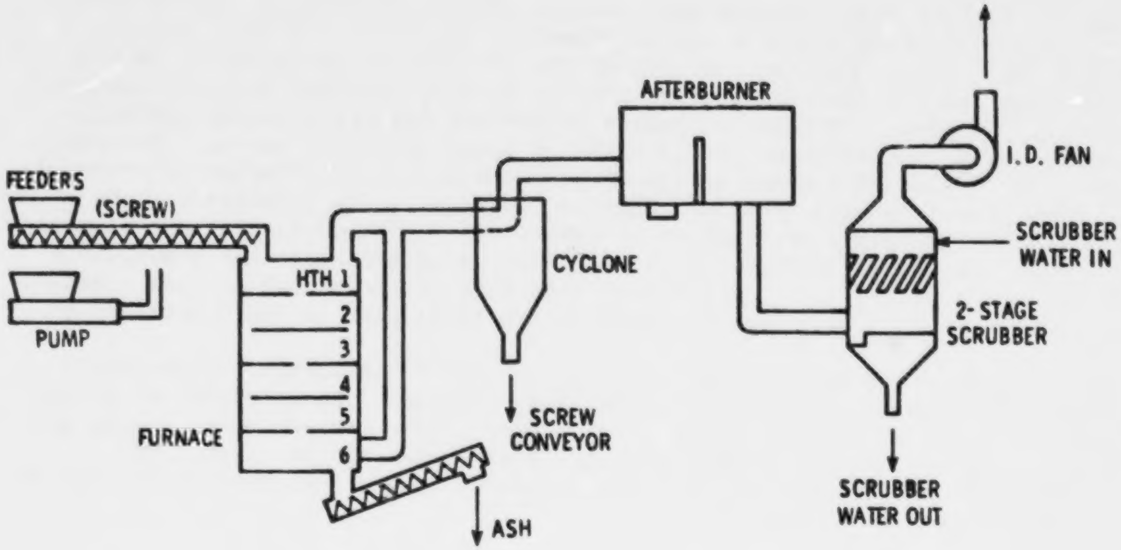
AFTERBURNER
I. D. FAN
FEEDERS
(SCREW)
PUMP
HTH 1
2
3
4
5
6
FURNACE
CYCLONE
SCREW CONVEYOR
ASH
SCRUBBER WATER IN
2- STAGE SCRUBBER
SCRUBBER WATER OUT

Figure 5-55. Incineration system with two-stage scrubber [40].

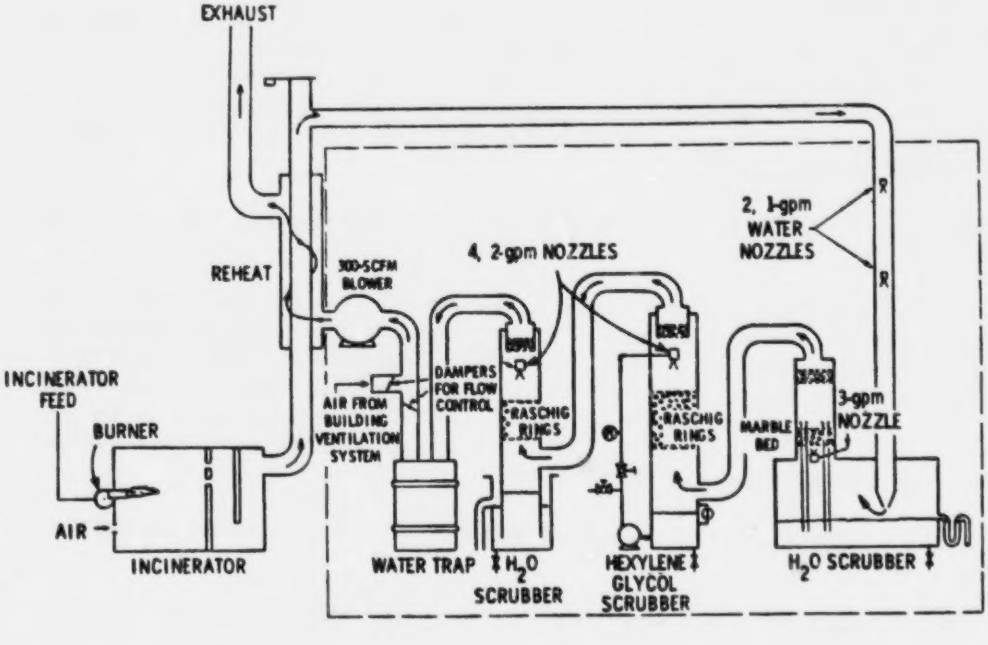
EXHAUST
REHEAT
300-SCFM BLOWER
4, 2-gpm NOZZLES
2, 1-gpm WATER NOZZLES
INCINERATOR FEED
BURNER
AIR
INCINERATOR
DAMPERS FOR FLOW CONTROL
AIR FROM BUILDING VENTILATION SYSTEM
RASCHIG RINGS
RASCHIG RINGS
MARBLE BED
3-gpm NOZZLE
WATER TRAP
H2O SCRUBBER
HEXYLENE GLYCOL SCRUBBER
H2O SCRUBBER

Figure 5-56. Incineration system with three-stage scrubber [41].

5.12.1.3 Ash--

Ash denotes the solid residue that remains after a material is incinerated. Ash produced during incineration is primarily inorganic and falls into two basic categories. Fly ash consists of the ash that is entrained in exhaust gases leaving the incinerator and which is usually captured in air pollution control equipment. Bottom ash refers to the ash remaining in the combustion chamber after incineration and is normally associated with inerts. The composition of the ash depends on the composition of the waste being incinerated and can therefore vary greatly. Because hazardous waste incinerators are designed for complete destruction of toxic organic compounds, the ash normally contains very little carbonaceous material. Solid materials not susceptible to oxidation (e.g., glass or ceramic) consitute the major ash species. Amount of ash produced is very small in relation to total mass of waste incinerated.

The relative proportion of fly ash to bottom ash is influenced by the waste composition and the incinerator design and operation. As expected, no bottom ash and relatively little fly ash result when liquid (except when liquids are from a complex chemical process that has inert materials in it or from a blending procedure that creates incompatible reactions that produce inerts) or gaseous wastes are incinerated.

5.12.2 Sampling and Analysis of Quench/Scrubber Water and Ash

Samples collected must be a representative sample of the whole water or ash. A representative sample for water can be collected by using various techniques and devices such as a coliwasa, automatic composite samplers like Isco, Manning, pond sampler, weighted bottle sampler, etc. Representative samples for ash can be collected by using devices such as a grain sampler, sampler corer, trowel or scoop, etc. Sampling devices and strategies are covered in detail in Chapter 3. Water samples are usually preserved because of any unstable species with the addition of appropriate preservatives. Where possible, samples are stored in a cool (4°C) and dark area prior to shipment to the laboratory for analysis.

The analysis of samples is directed primarily at determining the concentration of:

- Principal chemical species known to be present in the waste incinerated and believed to be hazardous. In some cases these will represent discrete chemical species such as nitrochlorobenzene and HCB. In other cases, such as those involving the incineration of tarry wastes from captan, rubber manufacturing and TDI, the analyses may have to be restricted to a general class of chemical species such as total organic chloride, total aromatic amine, etc.

- Primary decomposition products of waste such as chlorides, phosphates, sulfates, nitrates.

Solids can be analyzed via soxhlet extraction and water via liquid-liquid extraction.

5.12.3 Handling of Quench/Scrubber Wastewater

Quench water and scrubber effluents are normally combined for treatment and ultimate disposal. Depending on the scrubbing liquids used and the gaseous contaminants removed, wastewater may contain chlorides, fluorides, sulfites, sulfates, phosphates, bromides, and bromates, as well as particulate matter. Liquid waste streams containing sodium fluoride can be treated with lime or limestone slurry to yield the insoluble calcium fluoride. Sulfates, phosphates, and fluorides can be readily removed from the wastewater stream because of the low solubility of their calcium salts. Therefore, treatment normally includes clarification (to remove particulates), neutralization (to take care of any residual acid or base that may still be present), and dilution (to help control TDS levels). Particulates which are insoluble in the scrubber fluid become suspended solids in the scrubber wastewater. If the particulates dissolve in the scrubber fluid, they contribute to the wastewater's TDS level. Suspended solids in scrubber wastewater generally present little, if any, problems because their concentrations are usually less than 5 mg/L [39]. Suspended solids are usually removed by on-site settling ponds. Overflow from settling ponds can be recycled to scrubber.

Wastewater with either high or low pH levels is neutralized prior to final discharge (to a municipal sewer, or receiving stream). This is usually accomplished by adding either acid or base.

The high concentration of total dissolved solids (due to NaCl, $CaCl_2$ and in some cases the excess NaOH not used to neutralize HCl) is also reduced. This is usually accomplished by piping scrubber effluents to in-plant treatment systems or by diluting with other plant process streams and storing in a holding pond or lagoon.

In geographical locations with high evapotranspiration rates, solar evaporation could be used as a method for disposing of scrubber wastewater. For such a method to be considered environmentally acceptable, the scrubber wastewater would have to be devoid of potentially volatile materials which are hazardous. The ponds used for evaporation are periodically drained, and the accumulated sludge removed. Quench/scrubber effluents, evaporation sludge and ash treatment, and disposal options are illustrated in Figure 5-57.

For a discharge to a municipal sewer (publicly-owned treatment works - POTW), discharge must meet national general pretreatment standards and local POTW requirements, and must have approval from local POTW authority for such a discharge. By national pretreatment standards, pollutants introduced into POTW by any source of a nondomestic discharge are not to inhibit or interfere with the operation or performance of the works. The following pollutants may not be introduced into a POTW:

1. Pollutants which create a fire or explosion hazard in the POTW .
2. Pollutants which will cause corrosive structural damage to the POTW, but in no case discharges with pH lower than 5.0, unless the works is specifically designed to accommodate such discharges.

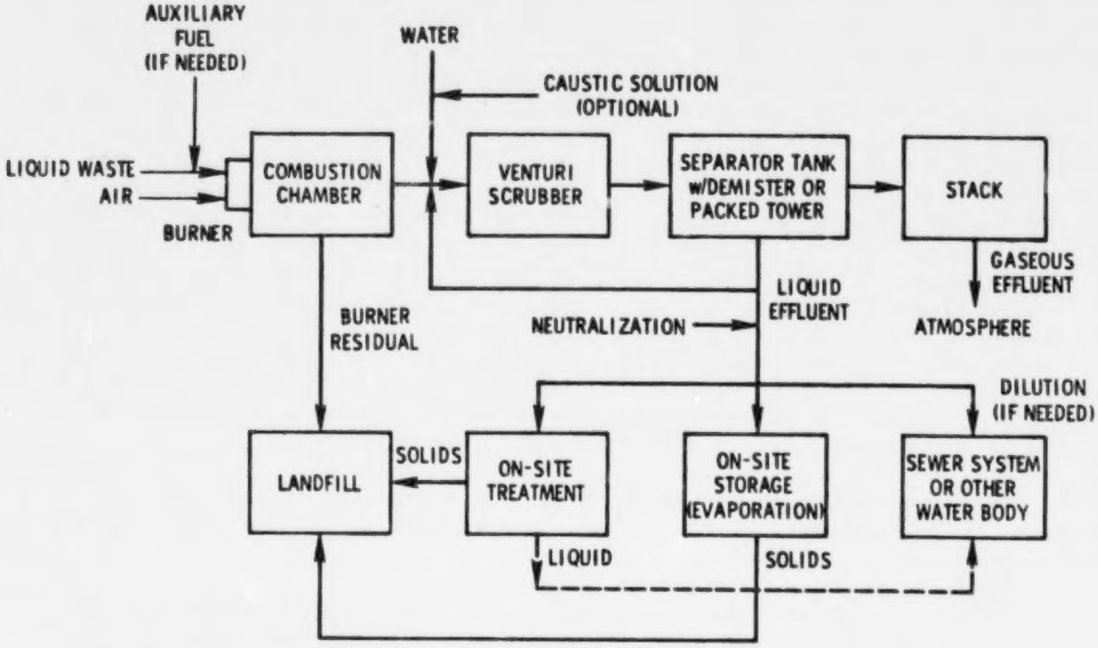
AUXILIARY FUEL (IF NEEDED)
WATER
CAUSTIC SOLUTION (OPTIONAL)
LIQUID WASTE
AIR
BURNER
COMBUSTION CHAMBER
VENTURI SCRUBBER
SEPARATOR TANK w/DEMISTER OR PACKED TOWER
STACK
GASEOUS EFFLUENT
ATMOSPHERE
LIQUID EFFLUENT
NEUTRALIZATION
BURNER RESIDUAL
DILUTION (IF NEEDED)
LANDFILL
SOLIDS
ON-SITE TREATMENT
ON-SITE STORAGE (EVAPORATION)
SEWER SYSTEM OR OTHER WATER BODY
LIQUID
SOLIDS

Figure 5-57. Incineration process with emissions treatment and disposal options [40].

3. Solid or viscous pollutants in amounts which will cause obstruction to the flow in sewers, or other interference with the operation of the POTW .

4. Any pollutant, including oxygen demanding pollutants (BOD, etc.), released in a discharge of such volume or strength as to cause interference in the POTW.

5. Heat in amount which will inhibit biological activity in the POTW resulting in interference but in no case heat in such quantities that the temperature at the treatment works influent exceeds 40°C (104°F) unless the works is designed to accommodate such heat.

Compliance with Prohibited Discharge Standards was required beginning August 25, 1978, except for the heat Standard which must be compiled with within 3 years, or August 25, 1981.

For a discharge to a receiving body, an NPDES permit will be required. Such a discharge has to meet with the limitations set in the permit. Wastewater may require costly treatments to meet the limitations set in the NPDES permit.

The sludges or other sediments collected from settling ponds, evaporation ponds, or other types of lagoons may contain unburned wastes or toxic trace elements (abstracted from the combustion gases as particulates, or formed as precipitates following chemical reactions occurring in the pond). Sludges from scrubber processes are chemical sludges; these are handled and treated carefully and possibly differently from municipal sludges. In order to insure the fewest adverse effects, they sometimes can be properly disposed of in an approved hazardous waste landfill in accordance with federal guidelines mandated by RCRA.

5.12.4 Handling of Ash

Bottom ash will contain primarily inorganic and carbonaceous compounds. Less than 3% of the total weight of carbonaceous compounds will be trace compounds, including heavy metals. These solids can be disposed of in landfills approved for hazardous wastes.

5.13 FUGITIVE EMISSIONS

Fugitive emissions are those which result from occurrences such as leaks in valves and piping, entrainment from open vents or piles of material, and transfer operations [2]. Such emissions must be minimized and/or eliminated at hazardous waste incineration facilities. This section discusses monitoring and techniques which may be used to control such emissions. Table 5-17 illustrates areas having fugitive emission potential.

The most likely areas of process oriented fugitive emissions are around rotating seals on kilns, piping joints and valves, ductwork leaks on the positive pressure side of induced draft systems, ash handling system leaks, and quench water scrubber liquid handling and treatment system leaks. For illustration purposes, these areas are indicated in Figure 5-58. In the preprocess area, handling, storage, and preparation of the waste for feeding into the incinerator are critical operations to watch for fugitive emissions. Post-process operations also can pose a problem, such as those which transport and treat residue streams emanating from quenching, scrubbing, and post-treatment of residue.

5.13.1 Significance of Observed Emissions

The two primary concerns regarding inspection and monitoring of fugitive emissions are protection of the personnel around the operation itself and the health and welfare of those residing outside the fence limits of the facility. Working conditions within the facility must be in accordance with the exposure constraints defined by OSHA regulations. Such emissions outside the facility area are governed by applicable ambient air regulatory constraints.

5.13.2 Fugitive Emission Control

Control of fugitive emissions is best accomplished through implementation of good engineering management practice. Initially, for a new facility a careful leak check is performed without hazardous components being treated in the system. Then during normal operation, visual inspection of all areas is performed

TABLE 5-17. POSSIBLE SOURCES OF FUGITIVE EMISSIONS FROM HAZARDOUS WASTE INCINERATOR SYSTEMS

WASTE PROCESSING AND FEED

- Waste shipping
- Waste unloading
- Waste loading to preparation/processing plant
- Waste processing
    - Crushing
    - Sizing
    - Washing
    - Drying
- Fine particulate removal or preparation for recycle
- Material transfer in waste processing plant
- Fugitives from loading/unloading storage bins
- Waste feed hopper backflow

WASTE INCINERATION AND POLLUTION CONTROL

- Waste feed
- Waste incineration/feed
- Air flow leaks in the incinerator furnace and associated systems
- Ash collection
- Stack flue gas particulate removal and disposal systems
- Ancillary equipment
    - Scrubber wastes/neutralization water
    - Dust collectors
    - Secondary combustion units (afterburners)
    - Gas/steam storage lines and transport lines
    - Water treatment units
    - Air coolers
    - Mixing chambers
- Ancillary equipment leaks

REMOVAL OR DISPOSAL METHODS

- Solids removal
- Ash transfer and storage
- Recycling systems
- Transfer lines for scrubber and cooler water
- Ash transport vehicles
- Ash transport
- Ash unloading
- Ash disposal

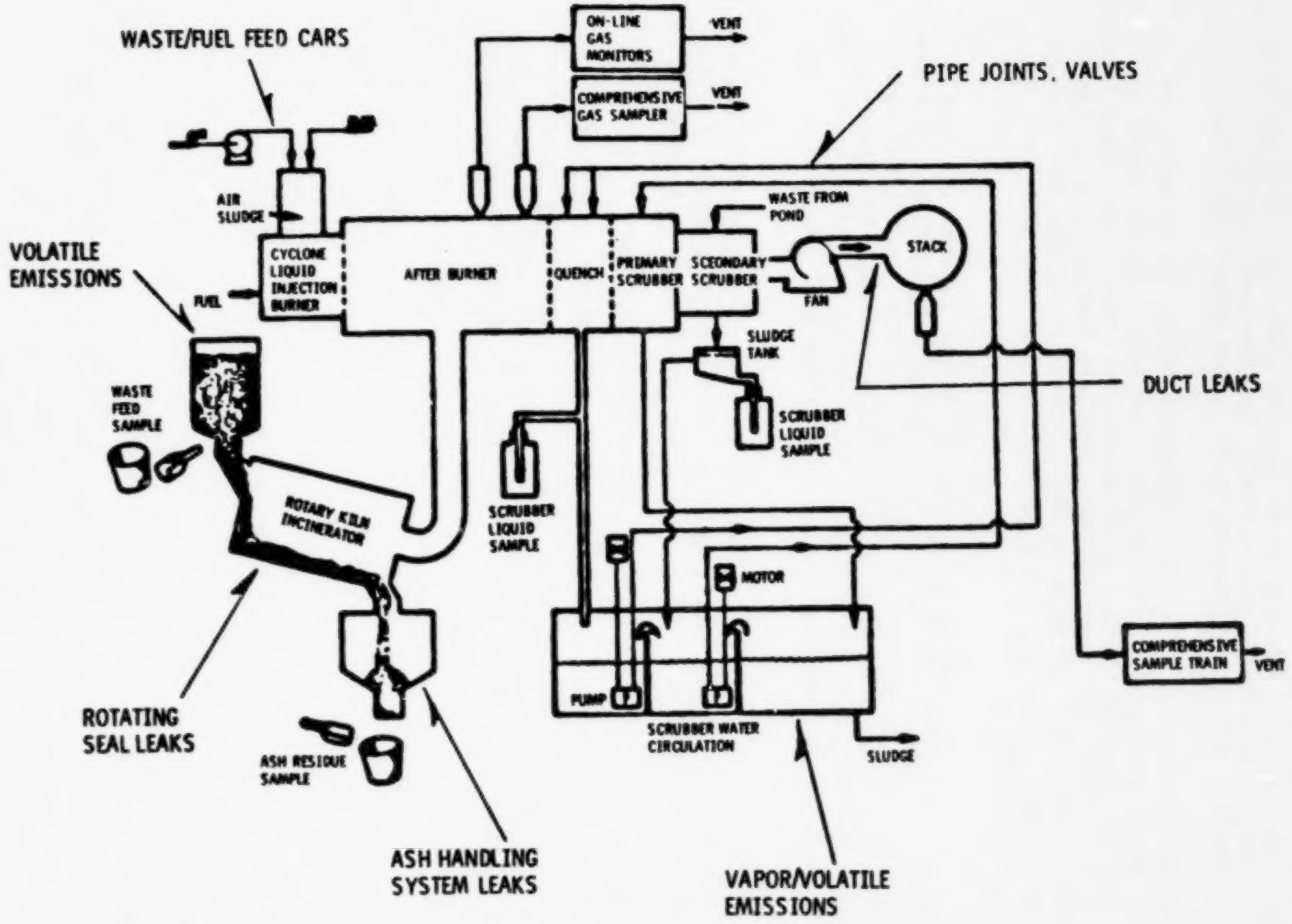
WASTE/FUEL FEED CARS
ON-LINE GAS MONITORS
VENT
COMPREHENSIVE GAS SAMPLER
VENT
PIPE JOINTS, VALVES
AIR
SLUDGE
WASTE FROM POND
VOLATILE EMISSIONS
CYCLONE LIQUID INJECTION BURNER
AFTER BURNER
QUENCH
PRIMARY SCRUBBER
SCEONDARY SCRUBBER
STACK
FUEL
FAN
SLUDGE TANK
WASTE FEED SAMPLE
DUCT LEAKS
SCRUBBER LIQUID SAMPLE
ROTARY KILN INCINERATOR
SCRUBBER LIQUID SAMPLE
MOTOR
COMPREHENSIVE SAMPLE TRAIN
VENT
PUMP
ROTATING SEAL LEAKS
SCRUBBER WATER CIRCULATION
SLUDGE
ASH RESIDUE SAMPLE
ASH HANDLING SYSTEM LEAKS
VAPOR/VOLATILE EMISSIONS

Figure 5-58. Possible process leakage areas.

to minimize the occurrence of undetected leaks. These visual inspections are then conducted regularly for any leaks, spills, odors, or other fugitive emissions. All automatic control system alarms and emergency shutdown features are also checked during the inspection to assure proper operation.

Any leak detected is recorded in a log. Immediate repair is accomplished if feasible. If immediate repair is not feasible, as judged by the owner/operator, a sample of the leak is then taken. If analysis shows that a hazardous component is leaking at a concentration above 10 ppm, immediate temporary or permanent repair should be affected. Maintenance data is recorded on the leak detection and repair survey log. This includes a recheck to make sure the repair was effective after maintenance.

For sources of fugitive dust emissions, several control alternatives are possible. Table 5-18 illustrates the types of activities which can generate dust (primarily around storage and ash handling), and the traditional techniques or types of equipment used for air pollution control. Two decisions need to be made initially for the control of particulate matter at a facility--the degree of control required, and whether the system will handle dust, wet or dry.

A wet-type particulate control system has limitations in that the wastewater created must be collected and treated for discharge and/or recycle. Recycle systems are preferred because of compliance with the NPDES permit program.

TABLE 5-18. CONTROL ALTERNATIVES FOR FUGITIVE DUST [42]

	Control techniques					
Type of activity	Baghouses/ scrubbers	Covers and enclosures	Spray systems	Encrusting agents	Wind breaks and physical arrangements	Paving or spray vehicle
Transfer points	X	X	X			
Conveyor belts		X	X			
Hoppers, dumpers	X	X	X			
Reclaimers			X			
Stockpiling equipment (bandwagons)			X			
Roads			X			X
Piles			X	X	X	
Bins, silos, bunkers	X	X				

5.13.3 Fugitive Emission Measurement Devices and Methodology

Source monitoring, area monitoring, and fixed-point monitoring are methods that can be used to detect fugitive emissions. Each of these is discussed below.

5.13.3.1 Area Monitoring--

To perform area monitoring, a path through the area to be monitored is predetermined so that one following the path will pass within a given distance (~3 ft) from all equipment within the area to be monitored. An instrument operator with a portable analyzer follows the predetermined path through the area and makes a complete survey around each piece of equipment. The operator must be careful that both the upwind and downwind sides of the equipment are sampled. If a concentration peak is observed, the location is recorded and a subsequent, more detailed survey made to pinpoint the exact source.

This is the same general procedure used for the regular visual inspection, but with a portable measuring instrument. An advantage of this method is that leaks can be detected quickly. Disadvantages include the possible detection of other emissions from outside the process area or improper readings due to wind gusts and wind direction variability. One outstanding disadvantage currently is that continuous portable monitoring equipment for measuring specific hazardous air pollutants are in the developmental stage and use would need to be examined carefully for appropriateness and utility.

5.13.3.2 Fixed-point Monitoring--

In the fixed-point methodology, analyzers are placed at specific points in the process area to monitor automatically for fugitive emissions. Individual samplers are placed either near specific pieces of equipment or in a grid pattern throughout the process area. If a concentration peak is observed, the operator then performs an individual component survey to detect the leak.

5.13.3.3 Source Monitoring--

In this methodology, leaks are detected by examining each individual component. Again, a portable detector is used. The instrument sample probe is moved along the component surface with care that both upwind and downwind areas are sampled. For sources such as drains, residue treatment tanks, and pressure relief valves, the probe is placed in the center and then along the periphery.

When no portable instrument is available, individual components can be en closed in a plastic bag (where practical). Any leaks accumulate in the bag and are exhausted through a sampling train designed to measure flow and prepare the sample for subsequent analysis by applicable laboratory techniques.

5.13.3.4 Current Instrumentation--

Particulate Measurements--Particulate sampling downwind of potential sources can be accomplished using high volume samplers. These devices consist of a pump and filter holder assembly encased in a weatherproof container. Ambient air is drawn across a preweighed filter membrane by a calibrated/feedback pump system. Filters are then weighed to obtain total mass particulate dust levels and analyzed for appropriate components.

Generally, a weather station is used to record wind speed, direction, temperature, atmospheric stability and barometric pressure over the sampling period.

Short-term ambient particulate levels can also be obtained by using either piezoelectric or beta attenuation monotors. These devices provide quick read-outs of ambient dust levels around a source. A number of readings can be obtained over a long period of time. Analysis of the collections on the substrate can be achieved as with the Hi-vol filter.

A particle size distribution of fugitive dust levels can be accomplished by attaching size - selective units (impactors) to the inlet of a high volume sampler. Particles are then collected on a substrate in each stage, depending upon the aerodynamic diameter of the incoming particles.

Particles less than 15 µm (EPA's definition of inhalable particulates) can be measured using dichotomous samplers. These devices consist of an elutriator in series with an impactor. The elutriator collects particles less than 15 µm and the impactor divides them into two fractions (<2.5 µm and >2.5 µm to 15 µm) which are collected on preweighed filters. Filters are then weighed and analyzed as necessary.

Particles can also be classified using a beta attenuation device by employing a small cyclone (inertial separator) in series with the pump. The cyclone collects the >10 µm particles, which then allows an attenuation readout of the <10 µm levels.

Measurement of Gases--Certain techniques for quantifying the fugitive gaseous emission levels from sources are available, which can obtain either (1) hydrocarbon-less-methane values or (2) if high enough concentrations exist, detection of individual components. In the latter case, a tandem-coupled gas chromatograph/mass spectrometer unit or GC alone would be employed for analysis with samples obtained by capture in a plastic bag for subsequent analysis.

Charcoal and porous polymer tubes connected to air pumps to draw ambient air across the median can be employed. The collection median is then solvent eluted for laboratory analysis.

Direct reading of ppm levels can be accomplished using Drager® tubes which are reactant impregnated substances. Ambient air is hand pumped through the collection median and the ppm levels read according to a color change.

Ambient total hydrocarbon levels can be measured using portable field gas chromatographs or hand-held flame ionization detectors. These devices operate on the same principle as the laboratory GC's except they have field use capabilities.

5.14 MATERIALS OF CONSTRUCTION

Materials of construction have been discussed for specific equipment throughout this chapter. This section is a repository of general information on various materials which may be encountered at a hazardous waste incineration facility. Included is information regarding trade names, corrosion resistances, and typical uses of both ferrous and nonferrous metals and other nonmetallic materials.

The general corrosion resistance properties are discussed. In most incinerator, receiving, storage, feed situations, and residue handling, the flow stream will contain contaminants, so corrosion problems will be maximal. This section will allow the permit writer to augment his knowledge of the materials involved and check the recommended application.

5.14.1 Metals

(1) Cast Iron - This material is found in many cast process components such as pump bodies, impellers, valve parts, etc. Cast iron is a general term applied to high carbon-iron alloys containing silicon. Common varieties are: gray, white, malleable, ductile, and nodular. The material is quite susceptible to oxidation or "rust".

Increasing the silicon content to over 14% produces an extremely corrosion resistant material; e.g., Duriron, which is very hard and resists erosion-corrosion (notable exception: hydrofluoric acid). The alloy is sometimes modified by the addition of 3% molybdenum; e.g., Durichlor or Durichlor 51, for increased resistance to hydrochloric acid and chlorides.

In addition to alloys using silicon and molybdenum, other alloys using nickel, chromium and copper also produce improved corrosion resistance. Copper addition causes the metal to better withstand attack from sulfuric acid. High nickel-chromium cast irons with and without copper; e.g., Ni-Resist and Ni-Hard, produce very tough castings to resist erosion-corrosion in near-neutral and alkaline solutions or slurries.

(2) Carbon Steel - Carbon steel is alloyed, in various combinations, with chromium, nickel, copper, molybdenum, phosphorous, and vanadium. Low-alloy steels (2% total maximum alloying elements or less) are generally the more corrosion resistant. However, like cast iron, it is very susceptible to rusting.

Steel products are cast and also readily available in sheet, plate, and structural forms, as well as in a variety of products. Steels can be easily field cut and welded.

(3) Stainless Steel - Stainless steel has the same versatility of usage as carbon steel, with greatly improved corrosion resistance. Desired corrosion resistant properties are produced by alloying at least 11 percent of chromium. The chromium is reactive, but sets up a passive film to inhibit further corrosion. The following is a brief description of the five types of corrosion resistant alloys most commonly used in chemical applications:

Type 304	The basic 18% Cr-8% Ni type for relatively mild corrosion resistance.
Type 316	The "18-8" type with 2.0/3.0% Mo for superior resistance to pitting and to most types of corrosion, particularly in reducing and neutral solutions.
Type 317	The "18-8" type with 3.0/4.0% Mo, which has moderately better resistance than type 316 in some conditions, such as high concentrations of acetic anhydride and hot acetic acid.
"20"	A 29% Ni-20% Cr steel with copper and molybdenum, developed specifically for resistance to sulfuric acid.
Ni-o-nel	A 42% Ni-21.5% Cr alloy with copper and molybdenum, developed to meet more severe corrosion and stress-corrosion conditions than can be handled by the stainless steels but where nickel-base alloys are not needed.

A popular fallacy is that stainless steels are generally resistant to all environments. Stainless steels do have widespread application in resisting corrosion, but also have limitations. In fact, under conditions involving chloride-bearing solutions and stressed members, stainless steels are subject to chloride stress corrosion cracking and thus are much less suitable than alloyed steels. Stainless steels are also more susceptible than regular steels to localized corrosion such as intergranular, crevice, and pitting attack.

Consequently, many corrosion failures have resulted from the indiscriminate use of stainless steels on the assumption that they were the "best." In practice, stainless steels represent a class of highly corrosion-resisting materials of moderate strength and cost that are the bulwark of the chemical process industries when used with discretion.

(4) Aluminum and Alloys - Next to carbon steel and stainless steel, aluminum represents a versatile metal for construction, available in cast form and sheet, plate, and structural forms and in a variety of commercially available process components.

Aluminum is reactive but develops a passive oxide film which protects it from further corrosion in many environments. This film remains stable in neutral and many acid solutions, but is attacked by alkalies. The passive film is produced after contact with the chemical environment, unless the film has been artificially produced through anodizing. Structural members are typically produced from high-copper alloys, whereas process components are usually constructed of the low-copper or copper-free alloys, which have better corrosion resistance.

(5) Magnesium and Alloys - A lightweight material often found on portable devices and vehicles, however one of the least corrosion

resistant. It must generally be physically separated from other metals or it will become a sacrificial anode for them. It is capable of forming a good passive film; however, the film breaks down in salty air conditions, necessitating special coatings or other surface preparations. Magnesium is susceptible to erosion-corrosion. It is much more resistant to alkalies than is aluminum. It is attacked by most acids except chromic and hydrofluoric. The corrosion product in HF acts as a protective film.

(6) Lead and Alloys - Used often on corrosion resistant applications in such forms as: sheet linings, solder, cable sheath, bearings, and piping. Lead forms protective films consisting of corrosion products such as sulfates, oxides, and phosphates. It is subject to erosion-corrosion because of its softness. Chemical-resistant lead, containing about 0.06% copper, is resistant to sulfuric, chromic, hydrofluoric, and phosphoric acids, neutral solutions, and seawater. It is rapidly attacked by acetic acid and generally not used in nitric, hydrochloric, and organic acids.

(7) Copper and Alloys - Copper alloys are found in pump bodies and impellers, process component bodies and parts, and in pipe tubing and fittings, tanks, bearings, wire and screen.

A good chemically resistant material, copper is not corroded by acids unless oxygen or other oxidizing agents (e.g., HNO_3) are present. Copper-base alloys are resistant to neutral and slightly alkaline solutions (exception: ammonia). Common alloys are: brass, bronze, and cupernickel. Bronze, aluminum brass, and cupranickel are stronger and harder than copper and brass and less subject to erosion-corrosion.

(8) Nickel and Alloys - A workhorse in severe corrosion applications, nickel and its alloys are found in many commercially available process components, expecially pumps, valve parts, and other critical process parts. Nickel is resistant to many corrosives and is a natural for alkaline solutions, found in many tough applications on caustics. It shows good resistance to neutral and slightly acid solutions. It is not resistant to strongly oxidizing solutions; e.g., nitric acid, ammonia. Among the common varieties:

Monel - natural for hydrofluoric acid

Chlorlmet 3 and Hastelloy C - two of the most generally corrosion-resistant materials commercially available

Chlorlmet 2 and Hastelloy B - very good in cases where oxidizing conditions do not exist

(9) Zinc and Alloys - Not a corrosion-resistant metal, chiefly used in galvanized steel.

(10) Tin and Tin Plate - Usually found as a coating and used in solder and babbit bearings, it is corrosion resistant, easily formed and soldered; and provides a good base for organic coatings. Tin has good resistance to dilute mineral acids in the absence of air, and many organic acids, but is corroded by strong organic acids; generally not used for handling alkalies.

(11) Titanium and Alloys - A newcomer to corrosion resistant construction, is available as castings in pumps, valves, and other process components. Titanium is a reactive metal which depends on a passive oxide film for corrosion resistance. Titanium has resistance to seawater and other chloride salt solution; hypochlorites and wet chlorine; and nitric acid. Salts such as $FeCl_3$ and $CuCl_2$, which tend to pit other metals do not corrode titanium. It is not resistant to relatively pure sulfuric and hydrochloric acids.

5.14.2 Nonmetallics

(1) Natural and Synthetic Rubbers - Rubber is an important process material with an extensive range of uses: hoses, tanks, tubing, gaskets, pump diaphrams and impellers, sheets, liners, etc. Rubber has excellent chemical resistance, and has been a standard for handling of hydrochloric acid containers. Generally, the synthetic rubbers have better chemical resistance than the natural rubbers. Vulcanization, the process of hardening rubber by adding sulfur and heating, can produce a wide range of hardnesses from soft gaskets to hard pump impellers. Corrosion resistance generally increases with hardness.

A wide variety of synthetic rubbers is available, including combinations with plastics. In developing the various products, plasticizer fillers and hardeners are compounded to obtain a large range of properties, including chemical resistance. Table 5-19 presents a list of brand names of plastic materials and the corresponding generic type of plastic.

Table 5-20 shows chemical resistance and other properties of commercially available rubber products. One of the newer elastomers which should be added to the list is Hypalon, which has excellent resistance to oxidizing environments such as 90% sulfuric acid and 40% nitric acid at room temperature.

(2) Plastics - Used extensively in chemical process applications as process component bodies and parts, tanks and tank liners, pipe, valves, tubing, and fittings, sheets, structurals, etc., plastics are high-molecular weight organic materials that can be shaped into a variety of useful forms.

When comparing plastics to metals, the former are softer and weaker, more resistant to chloride ions and hydrochloric acid, less resistant to concentrated sulfuric ad oxidizing acids such as nitric, less

TABLE 5-19. BRAND NAMES OF POLYMERIC MATERIALS

Material	Chart classification	Material	Chart classification
Aeroflex	Polyethylene	Mylar	Polyester
Alathon	Polyethylene	Nylon	Nylon
Araldite	Epoxy	Penton	Polyether
Avisco	Urea	Plexiglas	Methyl methacrylate
Bakelite	Phenolic	Plioflex	Vinyl
Beelte	Urea	Polythene	Polyethylene
Dacron	Polyester	Pro-Fax	Polypropylene
Durcon	Epoxy	PVC	Polyvinyl chloride
Durez	Phenolic	Resinox	Phenolic
Dypol	Polyester	Saran	Vinyl
Epon	Epoxy	Styron	Polystyrene
Excon	Polypropylene	Teflon	Fluorocarbon
Kel F	Fluorocarbon	Tygon	Vinyl
Lauxite	Urea	Vibrin	Polyester
Lucite	Methyl methacrylate	Vinylite	Vinyl
Lustrex	Polystryene	Viton	Fluorocarbon
Moplen	Polypropylene		

resistant to solvents, and have definitely lower temperature limitations.

Plastics, when subjected to corrosive environments do not fail as metals do. Rather than dissolving, they are degraded or corroded because of swelling, loss in mechanical properties, softening, hardening, spalling, and discoloration. Table 5-21 lists the properties of some commercially available plastics.

For ease of using this table, commonly used tradenames and other designations are listed here alphabetically in reference to the chart classification to which they belong:

(3) Other Nonmetallics - Used as materials of construction and lining of process systems:

Ceramics - compounds of metallic and nonmetallic elements; include magnesia, brick, stone, fused silica, stoneware, glass, clay tile, procelain, concrete, abrasives, mortar, high temperature refractories. Most ceramics exhibit good chemical resistance, with the exception of hydrofluoric acid and caustic.

Carbon and Graphite - often used for shaft seals; inert to many chemical environments; good resistance to alkalies and most acids; attacked by oxidizing acids such as nitric, concentrated sulfuric, and chromic; also attacked by fluorine, iodine, bromine, chlorine, and chlorine dioxide.

TABLE 5-20. PROPERTY COMPARISONS - NATURAL AND SYNTHETIC RUBBERS [12]

Property	Natural rubber	Butyl (GR-1)	Buna S (GR-S)	Neoprene	Nitrile (buna N)	Polyacrylic rubber	Silicone rubber
Hardness range (Shore "A")[a]	40-100	40-90	40-100	30-90	45-100	50-90	40-80
Tensile strength, psi[b]	4,500	3,000	3,500	3,500	4,000	1,500	900
Max. elongation,	900	900	600	1,000	700	200	250
Abrasion resistance[c]	Excellent	Good	Excellent	Very good	Excellent	Fair	Poor
Resistance to compression set at 158°F[c]	Good	Fair	Excellent	Good	Excellent	Good	Excellent
Resistance to compression set up to 2,500°F[c]	Poor	Poor	Excellent	Fair	Excellent	Good	Excellent
Aging resistance (normal temp.)	Good	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent
Max. ambient temp. allowable, °F	160	275	275	225	300	400	580
Resistance to weather and ozone[c]	Fair	Very good	Fair	Excellent	Fair	Excellent	Excellent
Resistance to flexing	Excellent	Excellent	Good	Excellent	Fair	Excellent	Poor
Resistance to diffusion of gases	Fair	Excellent	Fair	Very good	Fair		
Resilience	Excellent	Poor at low temperature; Good at high temperature	Fair	Very good	Fair	Poor	
Resistance to petroleum oils and greases	Poor	Poor	Poor	Good	Excellent	Very good	Good
Resistance to vegetable oils	Good	Good					
Resistance to nonaromatic fuels and solvents	Poor	Poor	Poor	Fair to good	Very good		Fair
Resistance to aromatic fuels and solvents	Poor	Poor	Poor	Fair	Good		Poor
Resistance to water and antifreezes[c]	Good	Good	Good	Fair	Excellent	Poor	Fair
Resistance to dilute acids	Good	Good	Good	Good	Good		
Resistance to oxidizing agents	Poor	Fair	Poor	Poor	Poor		
Resistance to alkali	Fair	Fair	Fair	Good	Fair		
Bielectric strength[c]	Excellent	Good	Excellent	Fair	Fair		
Flame resistance	Poor	Poor	Poor	Good	Poor		
Processing characteristics[c]	Excellent	Good	Good	Good	Good	Fair	Poor
Low temperature resistance[c]	Very good	Fair	Good	Fair	Good	Poor	Excellent
Tear resistance	Excellent	Excellent	Good	Good	Good	Fair	Poor

[a] 100 durometer reading is bone hard and indicates that ebonite or hard rubber can be made.

[b] Indicates soft-rubber type. Hard-rubber types run higher in value.

[c] These properties available in specific compounds.

TABLE 5-21. PROPERTIES OF COMMERCIALLY AVAILABLE PLASTICS [12]

Material	Acids		Alkalies		Organic solvents	Water absorption, %/24 hr	Oxygen and ozone	High vacuum	Ionizing radiation	Temperature resistance	
	Weak	Strong	Weak	Strong						High	Low
Thermoplastics											
Fluorocarbons	Inert	Inert	Inert	Inert	Inert	0.0	Inert	-	P	550	G-275
Methyl methacrylate	R	A-O	R	A	A	0.2	R	decomp.	P	180	-
Nylon	G	A	R	R	R	1.5	SA	-	F	300	G-70
Polyether (chlorinated)	R	A-O	R	R	G	0.01	R	-	-	280	G
Polyethylene (low density)	R	A-O	R	R	G	0.15	A	F	F	140	G-80
Polyethylene (high density)	R	A-O	R	R	G	0.1	A	F	G	160	G-100
Polypropylene	R	A-O	R	R	R	<0.01	A	F	G	300	P
Polystyrene	R	A-O	R	R	A	0.04	SA	P	G	160	P
Rigid polyvinyl chloride	R	R	R	R	A	0.10	R	-	P	150	P
Vinyls (chloride)	R	R	R	R	A	0.45	R	P	P	160	-
Thermosetters											
Epoxy (cast)	R	SA	R	R	G	0.1	SA	-	G	400	L
Phenolics	SA	A	SA	A	SA	0.6	-	-	G	400	L
Polyesters	SA	A	A	A	SA	0.2	A	-	G	350	L
Silicones	SA	SA	SA	SA	A	0.15	R	-	F	550	L
Ureas	A	A	A	A	A	0.6	A	-	P	170	L

Note: R = resistant, A = attacked, SA = slight attack, A-O = attacked by oxidizing acids, G = good, F = fair, P = poor, L = little change.

Wood -	Typical chemically resistant woods are cypress, pine, oak, and redwood; generally limited to dilute chemicals; strong acids, oxidizing cards, and dilute alkalies attack wood.

5.15 MISCELLANEOUS CONCERNS

5.15.1 Personnel Health and Safety

The health and safety of the public and of plant employees should be considered of major importance in any industrial installation design or operation. Although the greater part of this manual deals with possible injury to public health and property, the effect of plant emissions on the plant employees is also a primary concern. Often, plant employees in direct contact with the industrial processes for extensive periods of time are in the greatest immediate danger. This section will not attempt to define the multitude of work-related hazards facing hazardous waste incinerator workers, but will concentrate on these areas of concern: equipment for worker protection and procedures for worker protection [43].

- Synthetic Gloves - These provide skin protection for the hand and arm, as required. Synthetic means rubber, polyethylene, or other impervious materials. Full-arm-length gauntlets or sleeve protectors can also be used.

- Synthetic Aprons - Materials specified for synthetic gloves also apply to aprons. Disposable-type coveralls or laboratory coats may be preferred for many tasks at an incinerator facility.

- Respiratory Protective Devices - There are three types of these devices: (1) air-purifying respirators, (2) supplied-air respirators, and (3) self-contained breathing apparatuses.

  The air-purifying respirators utilize an aerosol filter for protection against particulate matter and/or a chemical cartridge for protection against certain known gases of vapors. The choice of cartridge is dictated by the hazard involved.

  The supplied-air respirators are supplied with air remote from the hazardous location, usually through a breathing-air manifold and hoses. The self-contained breathing apparatus is normally used only in emergency situations. Use only devices that are certified by NIOSH.

- Adequate Ventilation - Ventilation in an area must be sufficient to prevent harmful exposure to toxic materials. The threshold-limit value (TLV) for an individual chemical vapor or type of dust refers to the time-weighed concentration for a normal workday, under which it is believed that nearly all workers may be repeatedly exposed, day after day, without harmful effect. If this value is exceeded, then a "ceiling" value applies. This ceiling value should not be exceeded (emergency situations such as spills require the use of protective equipment). Exposure to concentrations above the TLV up to the ceiling value are not desirable, but are permitted as long as the overall eight-hour time-weighted average (TWA) does not exceed the TLV.

If inadequate ventilation is indicated (TLV is exceeded) for any operation or area, immediate use of a personal air-supply system is engaged. A permanent solution involving good engineering practices is then desirable and should be implemented as soon as possible.

- Full Suit - This is a suit that provides head-to-toe protection for the hazard involved.
- Line Breaks - Line breaks include broken flanges on lines not previously exposed to the atmosphere, and drained and repacking of valves and pumps, where there exists a potential for hazardous streams in concentrated form or under pressure. In this type of operation, the following protective equipment is usually required: full-rubber acid-suit consisting of rubber coat, rubber pants, acid gloves, rubber boots under the pants, and rubber hood.
- Repairs - Repairs apply to work performed on equipment or lines that handled hazardous waste streams, which had previously been opened to the atmosphere, and which have been drained and proven to be under no pressure. Since the hazardous potential still exists, goggles or an approved hood and gloves are typically required. After flushing with water--or a neutralizer agent where feasible--and the danger potential no longer exists, as determined by supervision, hazardous-material protection is no longer required. If the underfoot area is still puddled or wet from flushing and draining, rubber overshoes are usually required.

  If a pump is not delivering, and troubleshooting or priming is necessary, goggles and gloves with coat or apron are worn even though no breaks in the line have occurred.

5.15.2 Facility Housekeeping

Good housekeeping plays a key role in occupational health protection. Basically, it is another tool in addition to those other facility safeguards listed for preventing dispersion of dangerous contaminants. Housekeeping is always important; where there are toxic materials, it is paramount.

Immediate cleanup of any small spills of toxic material is a very important control measure. A regular cleanup schedule using vacuum cleaners or lines is the only truly effective method of removing dust from a work area. an air hose for blowing away dust is never used.

A high standard of housekeeping is the most important single factor in the prevention of fire. Many types of waste and rubbish are susceptible to spontaneous ignition. Practically all organic materials have a tendency to heat spontaneously. This tendency is greater for those containing oil, solids when pulverized, and vegetable or animal fibers, especially when wet. Many materials which are safe at room temperature will heat spontaneously after prolonged exposure to high temperatures, such as accumulations occurring in ducts or on heated pipes.

Accumulations of all types of dust are cleaned at regular intervals from overhead pipes, beams, and machines, particularly from bearings and other heated surfaces. It must be understood that all organic as well as many inorganic materials, if ground finely enough will burn and propagate flame. Roofs also are kept free from combustible refuse. Such cleaning perferably is done by vacuum removal, because blowing down with air may disperse dusts into dangerous clouds.

5.15.3 Maintenance

Testing is a prime activity in a maintenance program, particularly for a hazardous waste incineration facility. While alarm systems, spill-alert systems, and fail-safe devices are available, a testing program usually periodically creates situations which require fail-safe devices to demonstrate their operation. For instance, pressure testing of pipe, valves, and fittings along with hydrostatic testing of storage tanks will do this. Other tasks such as visual and electronic inspections will make up the remainder of a maintenance program and are included on prepared forms. These forms state the optimum timing for each inspection as well as the required frequency.

Incidences of excess emissions can be reduced by good operation and maintenance (O&M) practices and a comprehensive preventative maintenance program. With these practices, control equipment can provide maximum benefit.

While maintenance activities are not repetitive in the same manner as operating tasks, the maintenance function can be formalized. Available to facility management are maintenance management information systems, inventory and materials control systems, scheduling algorithms, work standards, indirect work measurement, and replacement theory.

A mechanism which is becoming more prevalent as equipment and technologies increase in sophistication is contract maintenance. Air pollution control equipment lends itself particularly well to this concept and appears attractive to new facilities which own several pieces of control equipment [44].

From the vendor's perspective, the advantages of providing a maintenance contract are:

(1) Close surveillance of the system's performance, especially during the warranty period.

(2) Immediate identification and troubleshooting of malfunctioning components.

(3) Avoidance of customer complaints.

(4) Operational experience that facilitates product improvement.

(5) Quick handling of emergency situations.

(6) A well functioning system that is the best recommendation for sales of additional systems.

From the user's point of view, the benefits of contract maintenance are:

(1) Plant personnel do not have to be thoroughly trained in equipment maintenance, thus allowing them to devote their time to process equipment.

(2) Technological troubleshooting and problem diagnosis are not usually in-house resources.

(3) Plant personnel do not necessarily have the knowledge to improve equipment performance.

(4) Plant personnel may lack awareness of alternative supplies and suppliers.

(5) Expenditures for larger crews, repair facilities, tools, and measurement instruments are reduced.

(6) Previous experience on similar equipment and applications can be used.

(7) Intrepretations of causes of component failure can be provided.

(8) Contract maintenance programs are more effectively regulated and administered than are in-house programs.

(9) Dirty and hazardous jobs do not have to be performed by plant personnal.

(10) Fluctuating workloads due to startup and seasonal variations can be handled easily.

An in-house regular maintenance/repairs program entails:

(1) Establishing a record system wherein periodic maintenance of each incinerator component is scheduled for completion by a qualified person.

(2) Cleaning, lubricating, and adjusting equipment by operating personnel as part of their daily or weekly task.

(3) Certifying that maintenance has been performed.

(4) Recording major repairs separately and completely.

(5) Thoroughly reporting each inspection, including condition of furnace, repairs performed, and expectation of future repairs or major overhaul.

(6) Inspecting components subject to rapid wear or damage weekly, at a time when such components are not being operated.

5.15.4 Firefighting/Emergency Personnel and Equipment

In addition to automatic sprinkler and extinguisher equipment, an incident confined to a limited area and that can be safely handled by a select emergency squad does not directly involve the overall emergency control program. If, however, such an incident should escalate beyond the capability of these forces, they have the authority to request the activation of the emergency program.

A fire emergency plan includes:

(1) An emergency squad composed of personnel from operations, maintenance, front office supervision, and guard force--specifically selected and trained in emergency control techniques and equipment.

(2) Emergency planning taking into account the plant's alarm system, communications, organization responsibilities, evacuation possibilites, available emergency equipment, mutual aid arrangements, and traffic control.

(3) Emergency crews engaged in continual training.

(4) Emergency squad members thoroughly trained in comprehensive first-aid treatment.

(5) Emergency squad members familiar with firefighting equipment.

The emergency squad composed of personnel from operations, maintenance, front office supervision, and guard force -- specifically selected, and trained in emergency control techniques and equipment. The exact number of employees on an emergency squad will vary depending on the potential hazard and size. Only if an emergency cannot be handled by this select squad, should the emergency control organization be activated.

Emergency planning also take into account the plant's alarm system, communications, organizational responsibilities, evacuation possibilities, available emergency equipment (and where it is located), dangers and emergency situations both inside and outside the plant (such as bomb threats), mutual-aid arrangements and traffic control. A manual containing the relevant information is prepared and distributed to those responsible for executing the plan. This is reviewed at least annually, and updated as needed.

Emergency crews must undergo continual training because the time available to respond to an actual emergency is usually quite limited. Furthermore, the infrequency of calls to action can, with time, erode the ability of crews to respond with the speed usually required. Crews are typically provided for all shifts, and be trained to handle all types of emergencies: fire, toxic-gas releases, chemical spills, serious injury, and personnel rescue.

Emergency-squad members are usually thoroughly trained in comprehensive first-aid treatment, including cardiopulmonary resuscitation, handling of breathing apparatus, and emergency rescue procedures, and are familiar with station and ambulance first-aid equipment. In addition, they learn the different types of fires, extinguishing agents, the proper protective clothing for firefighting, and become familiar with firefighting equipment, including hoses, nozzles, portable extinguishers, wheel units, fire trucks, and with the plant's fire-protection systems. Finally, field training in firefighting with protective clothing includes experience extinguishing "Christmas-tree," impingement, pan and spill, and other types of fires.

At a sprinklered property, the most important function of men assigned to the emergency organization is to assure at all times that the automatic sprinkler protection will operate as intended. At the start of the fire it must be made certain that sprinkler valves are open and fire pumps operating as needed; during the fire, that valves are not closed too soon; and after the fire, that opened sprinklers are replaced and protection restored promptly.

An emergency squad is designed to be capable of containing small fires, preventing them from developing into large, uncontrollable ones that can cause loss of life and property.

5.15.5 Stormwater Diversion

Stormwater drainage and other innocuous discharges are segregated and handled within the battery limits of the incinerator facility. These streams are normally collected and directed by pipe, drainage ditches, or area grading through one outlet from the area to a local feeder ditch. The single outlet or outfall also contain a spill control structure and gate which can be closed to contain contaminated drainage that may occur due to leaks or spills in the facility area. Feeder ditches generally border the plant sites along roadways and eventually drain outside the plant [45].

Facility process areas are usually paved and curbed or diked to contain leaks, spills, and washdowns, and these directed to a process sump area. The process sumps are pumped to the appropriate waste treatment facility.

Outlying facility storage tanks, pumps, and unloading facilities are curbed, diked, or paved for leak and spill control to prevent contamination of area drainage. The contained areas are then drained and valved to allow normal storm water drainage. These valves, which are normally closed, are opened for storm water drainage. In the event a contamination occurs, it is contained for subsequent treatment and appropriate disposal.

Other general features relative to plant drainage are:

(1) Valves used for the drainage of diked areas are normally manual, open-and-close design. The condition of the retained stormwater is determined before drainage, especially if such drainage of impounded waters goes into water courses and not into wastewater treatment plants.

(2) All plant drainage systems, if possible, flow into ponds, lagoons, or catchment basins designed to retain materials less dense than water. Consideration is also given to possible chemical reactions, if spilled chemicals are commingled.

(3) If plant drainage is not engineered as above, the final discharge of all in-plant drainage ditches is equipped with a diversion system that could, in the event of an uncontrolled spill, be returned to the plant for treatment, the objective being to work toward a closed-cycle system.

(4) Where drainage waters are chemically treated in more than one treatment unit, natural hydraulic flow is usually used. If pump transfer is needed, two pumps are typically provided, and at least one of the pumps is permanently installed.

5.15.6 Flue Gas Plume Aesthetics

Finally, the aesthetics of the flue gas plume should be considered. In a combustion gas which has been quenched with water, but from which no heat has been removed, the moisture content can be on the order of 0.5 lb of water vapor per lb of dry gas. This creates a moisture plume which can persist for a considerable distance depending upon ambient conditions. A water vapor plume does not violate any code but may be undesirable because of its visibility. A heavy moist plume falling on a non-plant area may be interpreted as a nuisance. This could be an important aesthetic consideration which must be specifically considered for each case. A stack gas moisture plume can be reduced by: (1) installing a cooling system for cooling recycled scrubbing water or by the use of cold once-through water for water cooling of the gases, or (2) installing a gas dehumidification and reheating system to reduce the relative humidity of the stack gas [17].

5.16 TECHNICAL ASSISTANCE

Other books and manuals which have applicability to overall facility design, operation, and monitoring for hazardous waste incinerators are:

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CHAPTER 6

ESTIMATING INCINERATION COSTS

6.1 INTRODUCTION

This chapter provides the user with tools for assessing the costs associated with: (1) hazardous waste incineration facilities, (2) the most likely modifications to the equipment and/or operations of such facilities, and (3) trial burns. The modifications may be necessary for a facility to comply with applicable environmental regulations, and they are closely related to the hazardous waste incineration design and operating criteria defined in Chapter 4. The trial burn may be necessary when uncertainties are present relative to the ability of a given facility to burn a given waste while preventing hazards to the environment and public health.

The cost data presented in this chapter are intended to be used only for first-cut estimating purposes and are believed to be accurate to no more than ±50%. It is impossible to present more accurate data in this chapter for three reasons.

1. All incinerators are not alike. Differences in design, operation, and in the waste burned in a given incinerator have a significant effect on costs.
2. There is a lack of agreement about exactly what costs should be considered in determining the capital and operating costs of hazardous waste incineration facilities.
3. Industry has had only limited experience with incinerating bulk quantities of hazardous waste.

Work in this area is continuing at EPA and, with the cooperation of industry, EPA will hopefully be able to provide more accurate and comprehensive data in the future. The user is encouraged to develop and use estimates which represent the conditions of a given facility more accurately and to consult references cited in this chapter and other resources for additional data on costs related to hazardous waste incineration.

The chapter contains five more sections. Section 6.2 is a generalized discussion of techniques for estimating capital and operating costs. Section 6.3 presents capital and operating cost estimates for liquid injection and rotary kiln hazardous waste incinerators, and air pollution control devices. Sections 6.4 and 6.5 discuss those costs associated with incineration facility modifications and trial burns, respectively. Finally, Section 6.6 provides references for further assistance.

6.2 GENERAL PRINCIPLES OF COST ESTIMATION [1]

Several methods of varying degrees of accuracy are available for estimating the capital and operating costs of incineration and air pollution control systems. These methods range from presenting overall installed costs on a per unit basis, to detailed cost estimates based on preliminary designs, schematics, and contractor quotes. The least accurate method is the equating of overall capital costs to a basic operating parameter such as tons per hour or cfm. An example is a typical installed cost for a fabric filtration system of approximately $7/cfm. This figure is developed from average costs of many installations which may range from $3/cfm to $12/cfm. The low end of the range might represent an installation using standard equipment installed by plant personnel. The high end of the cost range may represent a system designed for: 1) the inclusion of standby equipment and redundant systems, 2) provisions for safety, 3) fully automated operation with complex controls, and 4) expensive materials of construction or other custom features. These factors affect both equipment and installation costs, and therefore the degree of accuracy produced using such an estimating method would, at best, provide accuracies in the "order of magnitude" category (probable accuracy of +50%, -30%) [1]. The cost information in this chapter is presented in terms of Btu/hr and acfm and is intended only for first-cut estimating purposes.

The detailed cost estimate, in turn, can produce accuracies of ±5 percent depending on the amount of preliminary engineering involved. These estimates take many months of engineering effort and require process and engineering flow sheets, material and energy balances, plot plans, and equipment arrangement drawings before a cost estimate can be developed [1].

6.2.1 Capital Costs

Capital costs consist of the delivered equipment costs for major equipment items and all the auxiliary equipment and appurtenances plus the direct and indirect costs of installation. The delivered equipment costs represent a firm cost, since these are obtainable from the supplier's quoted prices or from curves compiled from average costs for the specific type of equipment. The cost of installation can vary substantially from one pollution control system to another depending on such features as: 1) the degree of assembly of the control device; 2) the geographic location of the installation; 3) the topography of the land site; and 4) the availability of utilities [1].

6.2.1.1 Purchased Equipment Costs--

The purchased equipment costs represent the delivered costs of the control device, auxiliary equipment, and instrumentation. These costs are developed by first establishing the design and operating characteristics of the equipment that will satisfy the process requirements and then using graphs and/or tables of historical cost data for the various items. The typical cost factor for instrumentation can be considered as 10% of the equipment costs. Freight costs within the U.S. are generally 5% of the equipment cost although a cost adjustment must also be included for unusually remote or distant sites. The purchased equipment costs, which include the F.O.B. equipment cost, instrumentation, freight and taxes, then become the basis for determining the direct and indirect installation costs. This is done by multiplying the appropriate factor for each element by the purchased equipment cost [1].

6.2.1.2 Installation Costs--

Installation costs consist of the direct expenses of material and labor for foundations, structural supports, handling and erection, electrical, insulation, painting, site preparation, and facilities; plus the indirect expenses for engineering and supervision, construction and field expenses, construction fees, start up, performance tests, model studies, and contingencies. In considering the direct costs, site preparation, buildings, and facilities are items that have little or no relationship to the cost of the purchased equipment. Therefore, some cost adjustment, must be used. Although handling and erection are related to equipment costs, some adjustment must also be made for either field erection or factory assembly as well as the type of installation, that is, new or retrofit of an existing process [1].

Variations in the indirect expenses can be substantial since items such as engineering, construction fees, and contingencies are related to contracting methods and the overall magnitude of the project rather than the equipment costs. These items all require some adjustment based on system size and contracting arrangement. Other cost items such as model studies may appear in unusual circumstances such as large electrostatic precipitator systems or other systems where the level of previous experience may be limited [1].

6.2.2 Annualized Costs

Typical annualized costs consist of the direct expenses of labor and materials for operation and maintenance, the cost of replacement parts, utility costs, and waste disposal; plus the indirect costs of overhead, taxes, insurance, general administration, and capital recovery charges. Unit costs can vary significantly from installation to installation. In the case of pollution control systems, waste disposal costs are only applicable to those systems where the collected pollutant has no value and must be removed to a disposal site [1].

The indirect operating costs are basically related to the capital investment with the possible exception of overhead. Overhead expenses include, for example, the cost of employee fringe benefits, medical and property protection, and cafeteria expenses and are accounted for as a percentage of direct salaries or payroll [1].

The operating costs must be adjusted for any credits that are obtained from the reuse or sale of recovered products or from the recovery of heat and energy from the process. Credits such as solvent recovery can significantly offset control expenses and must be considered as an important factor in an accurate cost analysis [1].

6.2.2.1 Direct Operating Costs--

Labor and material costs for operation and maintenance vary substantially between plants due to the degree of automation, equipment age, and operating schedule. Some generalizations must be made to develop a reasonable method of estimating these costs. Normally these costs represent from 2 to 8 percent of the total annualized costs with the remainder reflecting the cost of utilities and capital charges. In general, operating labor and supervision will be reduced with increased system automation. Small systems which operate intermittently or on demand may require a full-time operator for start-up, control, and shutdown while the system is in operation. In contrast, larger automated systems operating continuously may only require a short period per shift for monitoring purposes. The total annual labor cost is also a function of the number of 8-hour operating shifts per year. Small plants may be expected to operate one shift per day, five days per week, and fifty weeks per year while large plants, such as those in the basic metals, petroleum, and chemical industries, would be expected to operate three shifts per day for 365 days. The operator labor, therefore, should be estimated on a man-hours per shift basis for the particular types of system. For large, automated, continuously operated pollution control systems, the operating labor can be estimated.

When periodic replacement of major parts is required, such as the replacement of filter bags in a fabric filter, the labor cost for replacement should be equal to the material cost of the replacement parts. For small- to medium-size systems where the installed cost is approximately $100,000, or less, the total cost of maintenance is assumed to be 5 percent of the installed capital cost [1].

The annual cost of replacement parts represents the cost of the parts or components divided by their expected life. Replacement parts are those components and materials such as filter bags and catalyst which have a limited life and are expected to be replaced on a periodic schedule. Estimates of the life of pollution control equipment and related replacement parts, such as are shown in Table 6-1, are based on qualitative judgement of the type of application, maintenance service, and duty cycle. The guideline for average life represents a process operating continuously with 3 shifts per day, 5 to 7 days per week, handling moderate concentrations of non-abrasive dusts or non-corrosive gases. The guideline for low-life applications is based on a continuous process handling moderate- to high-temperature gas streams with high concentrations of corrosive gases or abrasive dusts. Applications having high life expectancies for parts and equipment would be those operating intermittently or approximately one shift per day with gas streams with low concentrations and at ambient gas stream temperatures [1].

6.2.2.2 Indirect Operating Costs--

The indirect operating costs include the cost of taxes, insurance, administration expenses, overhead, and capital charges. Taxes, insurance and administration can collectively be estimated at 4 percent of the capital cost while overhead charges can be considered as 80 percent of the labor charges for operation and maintenance of the system. The annualized capital charges reflect the costs associated with capital recovery over the depreciable life of the system and can be determined as follows [1]:

TABLE 6-1. ESTIMATES OF LIFE OF MATERIALS, PARTS, AND EQUIPMENT FOR AIR POLLUTION CONTROL SYSTEMS [1]

Item	Length of service, years		
	Low	Average	High
Materials and Parts			
Filter bags	0.3	1.5	5
Catalyst	2	5	8
Refractories	1	5	10
Equipment			
Electrostatic precipitators	5	20	40
Venturi scrubbers	5	10	20
Fabric filters	5	20	40
Thermal fume incinerators	5	10	20
Catalytic fume incinerators	5	10	20

$$\text{Capital recovery cost} = (\text{capital costs}) \times \frac{i(1+i)^n}{(1+i)^n - 1}$$

where i = annual interest rate
n = capital recovery period.

6.3 CAPITAL AND OPERATING COSTS FOR HAZARDOUS WASTE INCINERATION FACILITIES AND AIR POLLUTION CONTROL DEVICES [2-4]

6.3.1 Hazardous Waste Incinerators

Information presented in this subsection aids in determining whether capital and operating costs of the hazardous waste incinerator are in the expected range compared to similar incinerators. All costs are shown as a function of incinerator heat load and are grouped as follows: (1) rotary kiln incinerator with and without energy recovery, and (2) liquid injection incinerator with and without energy recovery.

6.3.1.1 Capital Investment for Hazardous Waste Incinerators--
Figures 6-1 and 6-2 show the total capital investment for a rotary kiln incinerator and for a liquid injection incinerator, respectively. These costs are based on references 2 through 4, representing incineration of rubber wastes, polyvinyl chloride waste, and ethylene. The estimated capital investments represent costs for "grass roots" plant installation excluding land costs. Chart accuracy is anticipated to be ±50% of mid-1980 costs. The incinerator capacity in Btu/hour includes the heat release rate from the auxiliary fuel as well as that of the waste being burned.

The rotary kiln incineration system costs include those for the material handling building, the rotary kiln primary combustion chamber, an afterburner,

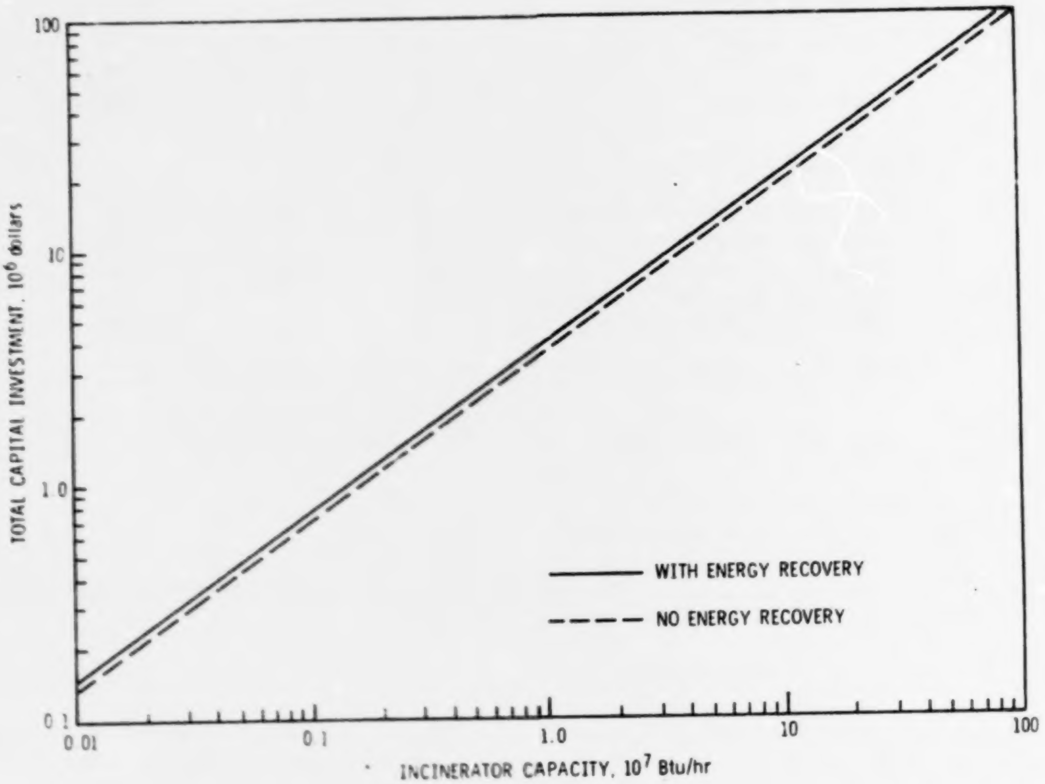

Figure 6-1. Total capital investment* for a rotary kiln incinerator [2-4].

*Expressed in June 1980 dollars, actual costs expected to be within ±50% of values from curve.

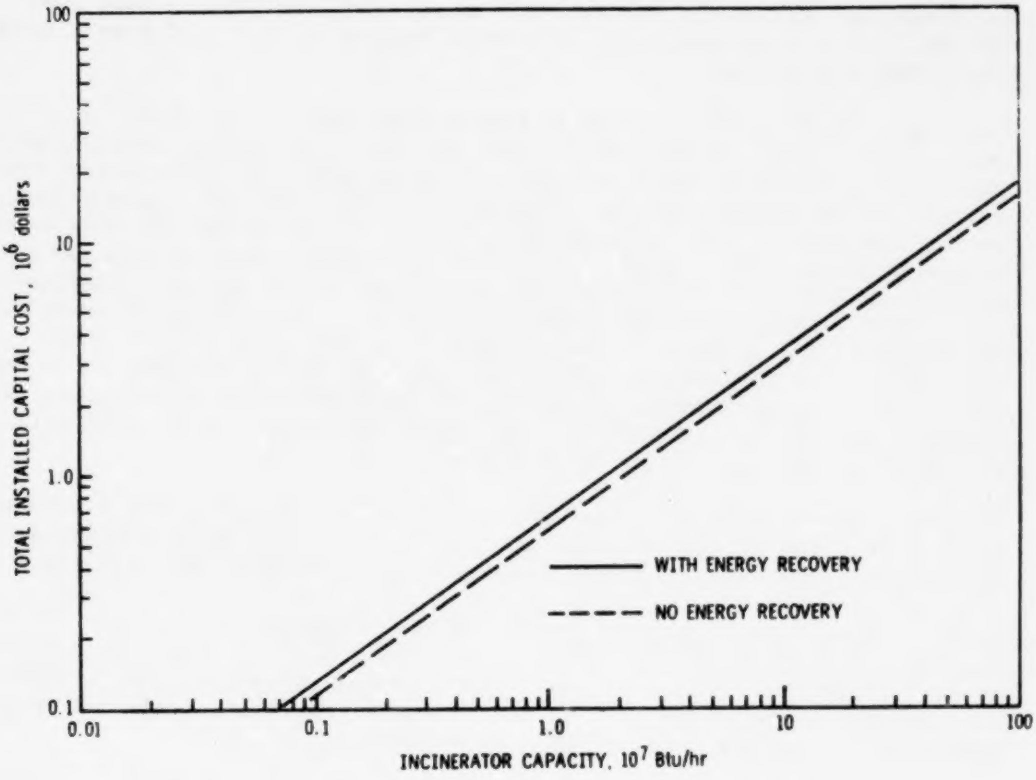

Figure 6-2. Total capital investment* for a liquid injection incinerator [2-4].

*Expressed in June 1980 dollars, actual costs expected to be within ±50% of values from curve.

a water quench chamber, a high energy venturi scrubber, a demister, a fan, stack, a scrubber water neutralization system (for HCl from the combustion of vinyl chloride waste), and associated equipment. The capital costs for rotary kiln incinerator systems were calculated by adding the costs for Purchased Equipment Items (PEI) (rotary kiln incinerator and afterburner equal 50 to 70% of PEI); adding 15 percent to get Installed Equipment Cost (IEC); adding costs for piping (40% IEC), building, structures, and foundations (35% IEC), and electrical and instruments ($50,000) to get Total Physical Plant Cost (TPPC); and then adding 50% of TPPC for engineering, construction, and contingencies. All costs were adjusted to June 1980 dollars. In sizing equipment, on-stream factors of 0.8 to 0.9 were used (7000-7900 hours/year).

The liquid injection incineration system costs include those for the building, waste storage tank, automated feed system, fuel oil storage tank, liquid injection incinerator, high energy venturi scrubber, scrubber water supply system, and pH control system. The capital costs for the liquid injection incinerator system were calculated by adding the costs for the Purchased Equipment Items (PEI), (liquid injection incinerator and venturi scrubber equal 40 to 60% PEI); adding 10% PEI for labor to get Installed Equipment Cost (IEC); adding costs for piping (90% IEC), buildings, structures and foundations (30% of IEC), and electrical (50% IEC) to get Total Plant Cost (TPC); and then adding 30% of TPC for overhead to get Total Erected Cost (TEC) and then adding 20% of TEC for engineering and contingencies to get Total Capital Investment. All costs were adjusted to 1980 dollars, and an on-stream factor of 0.8 to 0.9 was used.

While the useful life of these facilities was not specifically discussed in literature cited, a general rule of thumb of 20 years seems appropriate. This is the life experienced by most petroleum and petrochemical facilities.

6.3.1.2 Operating Costs of Hazardous Waste Incinerators-- Figures 6-3 and 6-4 exhibit annual operating costs for rotary kiln and liquid injection incinerators, with and without energy recovery. Due to savings realized by making steam on site, total annual operating costs are generally lower when an energy recovery unit is employed.

The term "fuel" is used in sources cited to indicate auxiliary or supplemental fuel (usually No. 2 fuel oil) used to raise combustion zone temperatures. The need for supplemental fuel is determined by the heating value and/or water content of the waste.

6.3.2 Air Pollution Control Devices [5]

An important cost-related item that should not be overlooked in using incinerators for hazardous waste disposal is air pollution control to meet Federal, state, and local regulations. The combustion of the waste in the incinerator may not end the pollution problem, since dust, fumes, smoke, and particulate emissions may be combustion byproducts requiring removal hardware. Many of the air cleanup devices use recirculating water, which in turn may require water pollution control devices or ultimate chemical treatment. These steps can

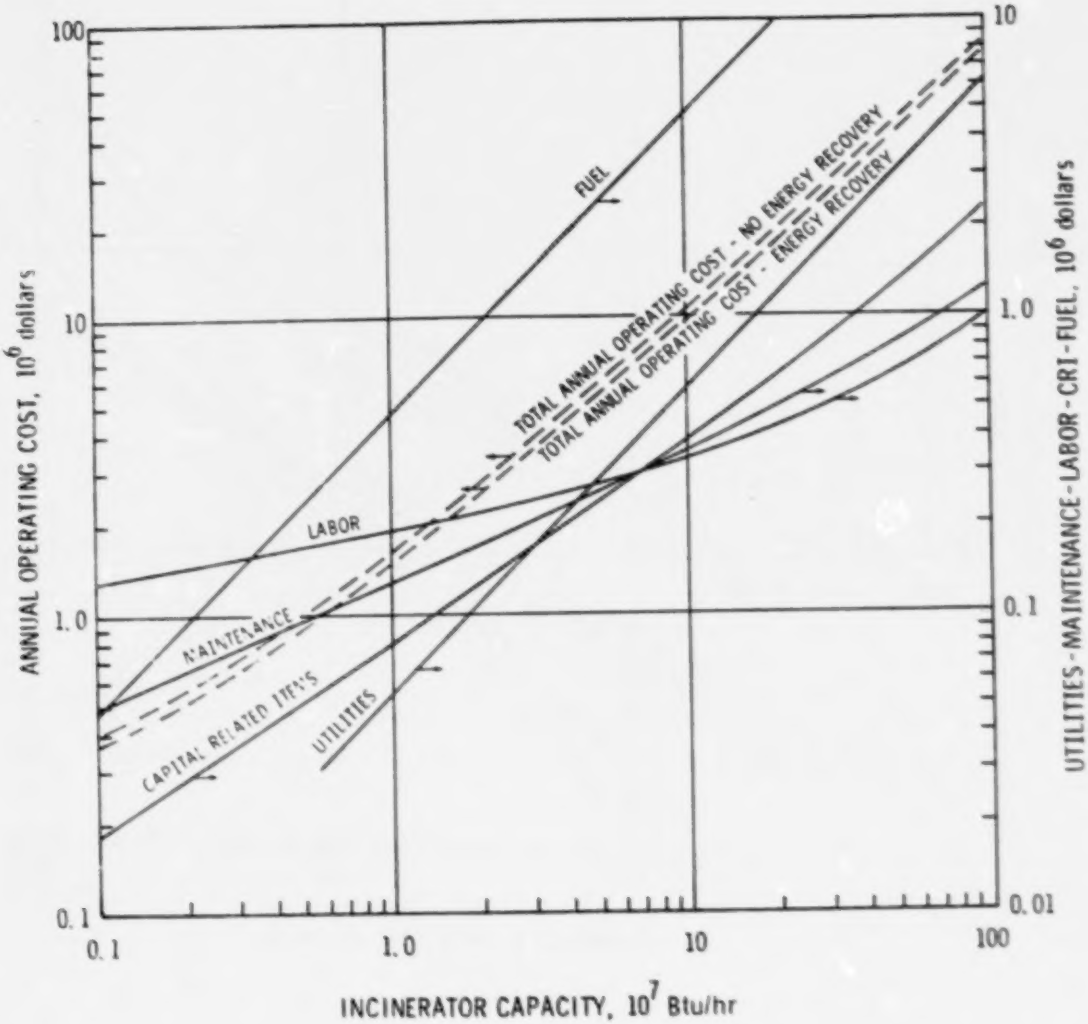

Figure 6-3. Total annual operating cost for a rotary kiln incinerator [2-4].

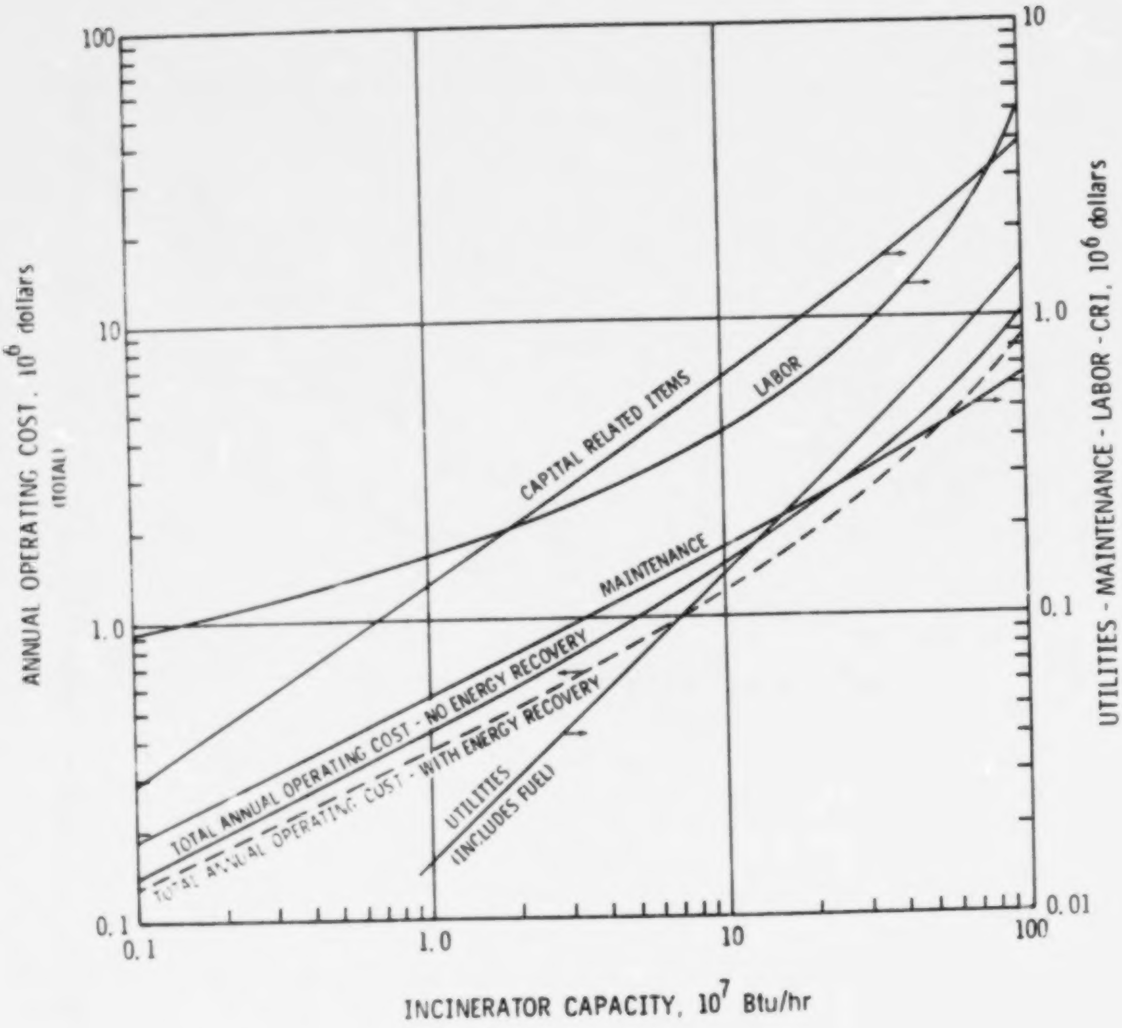

Figure 6-4. Total annual operating cost for a liquid injection incinerator [2-4].

add significant investment and operating costs to the overall cost of the incineration process.

Pollutants that are likely to show up in the exhaust gases include: flyash and other noncombustible particulates, sulfur and nitrogen oxides, acidic gases, odors, and smoke. Figures 6-5 through 6-13 give capital and annualized costs for fans, electrostatic precipitators, fabric filters, mechanical collectors, incinerators, and venturi scrubbers.

6.3.2.1 Air Pollution Control Device Capital Installed Costs--

A number of cost curves (Figs. 6-5 through 6-13) have been developed that provide conceptual or study estimates of the capital and annualized costs of complete air pollution control systems. These curves presented provide costs for grass-roots installations. A retrofitted installation generally costs 10 to 30 percent more than a grass-roots installation and, depending on specific difficulties at a given site, the costs can be calculated on the basis of the latter percentage.

Figures present these costs based upon gas volume through the major air pollution control device types. The gas volume generated under a given set of waste and combustion conditions can be determined through the methods described in Chapter 4. For reference purposes, as a rough approximation, the following relationship may be used:

$$\frac{\text{scf of SA}}{\text{lb of feed}} = \frac{\text{Gross heating value of fuel (Btu/lb)}}{100}$$

where SA ≡ stoichiometric air.

6.3.2.2 Electrostatic Precipitator--

Figure 6-7 presents cost curves for systems utilizing an electrostatic precipitator housed in an insulated, carbon steel shell. The assumption is made that the uncontrolled gas stream is normally vented to a stack. Thus, the necessary fan and ductwork are considered part of the process. Costs are presented for three levels of control efficiency based on medium- and high-reactivity dust. For a given collection efficiency, high-resistivity dust requires a greater SCA (specific collection area) and the cost of the ESP is thus increased. For purposes of estimating equipment costs, plate area was calculated according to the Deutsch equation with partical drift velocities of 0.036 m/s for high-resistivity dusts and 0.086 m/s for low-resistivity dusts. Dusts such as fly ash from low-sulfur coal combustion and cement kiln dust have high resistivity.

6.3.2.3 Fabric Filters--

Fabric filters are commonly used across a broad range of exhaust gas volumes. Low-temperature and low-volume exhaust streams from conveyor transfer points are normally vented to a fabric filter. On the other hand, high-temperature and high-volume exhausts from electric arc furnaces are also often vented to a fabric filter. Figures 6-8 and 6-9 present cost curves for a variety of fabric filter applications. Costs are presented for filters utilizing each type of

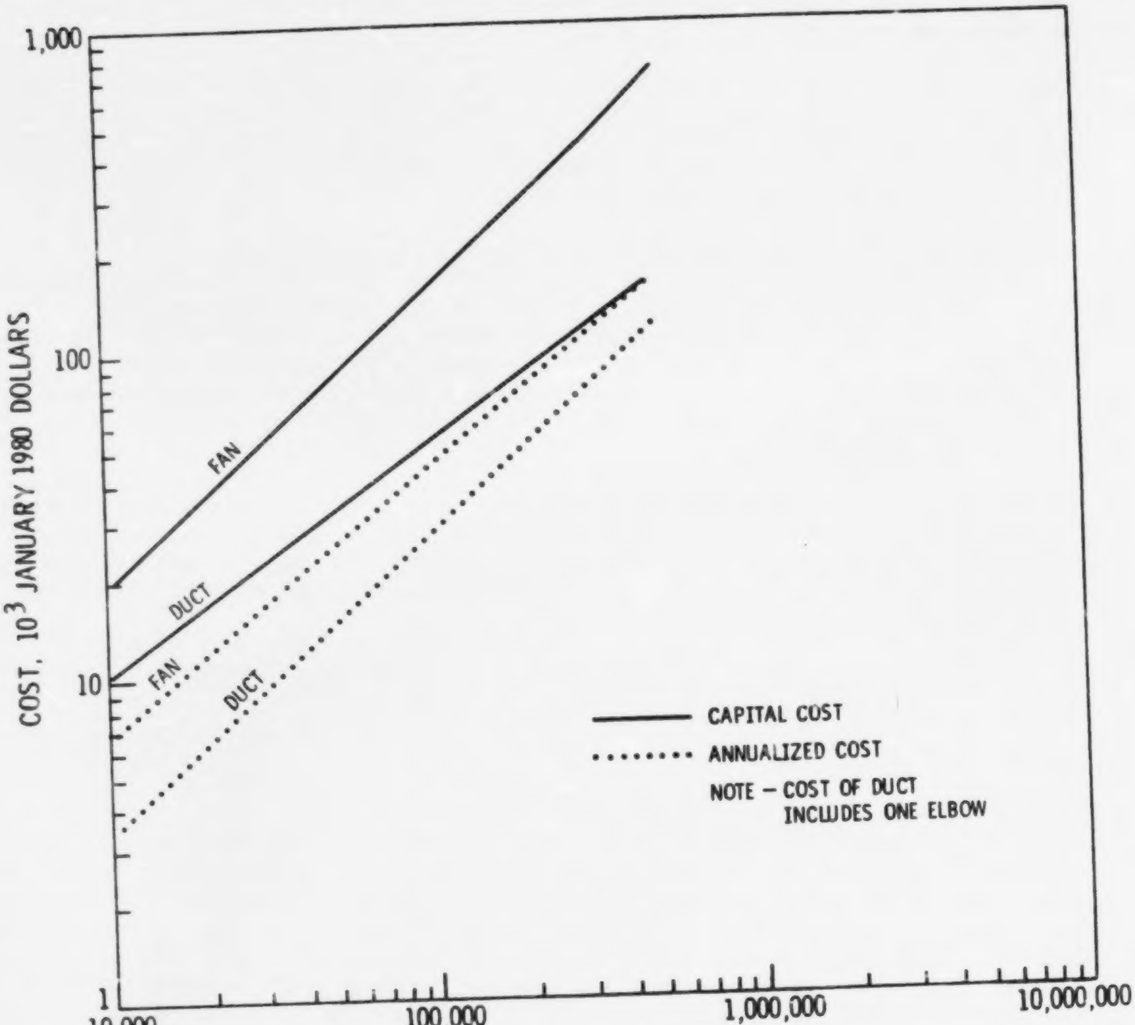

Figure 6-5. Capital and annualized costs of fans and 30.5 length of duct.

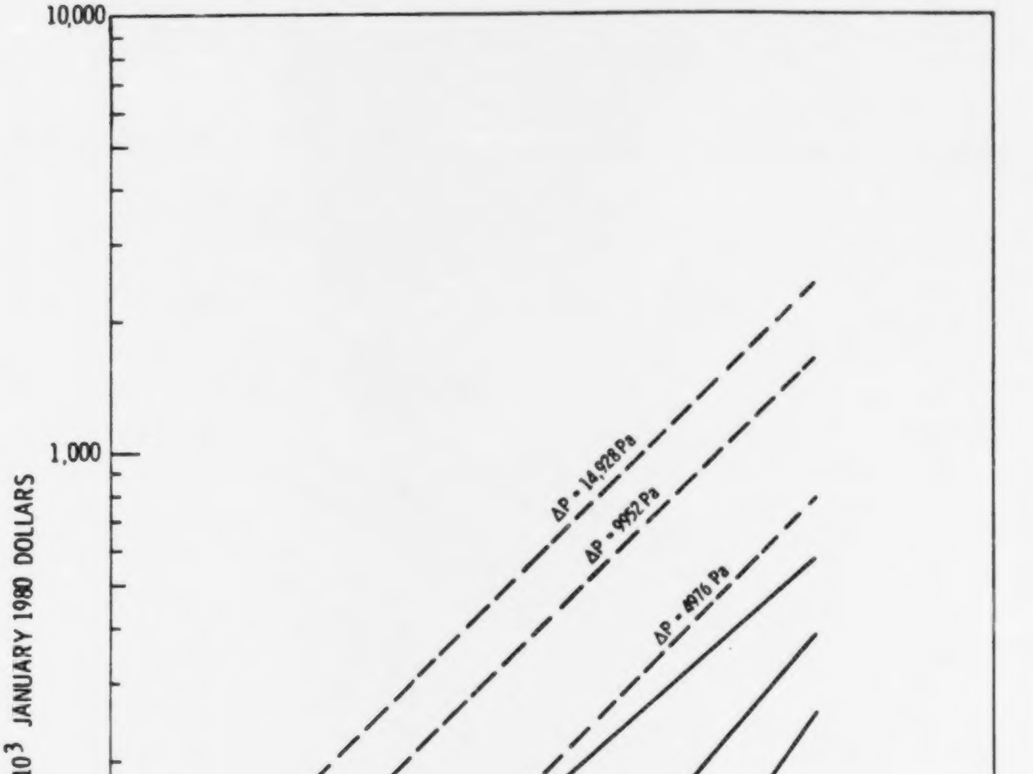

Figure 6-6. Capital and annualized cost of fan driver for various head pressures.

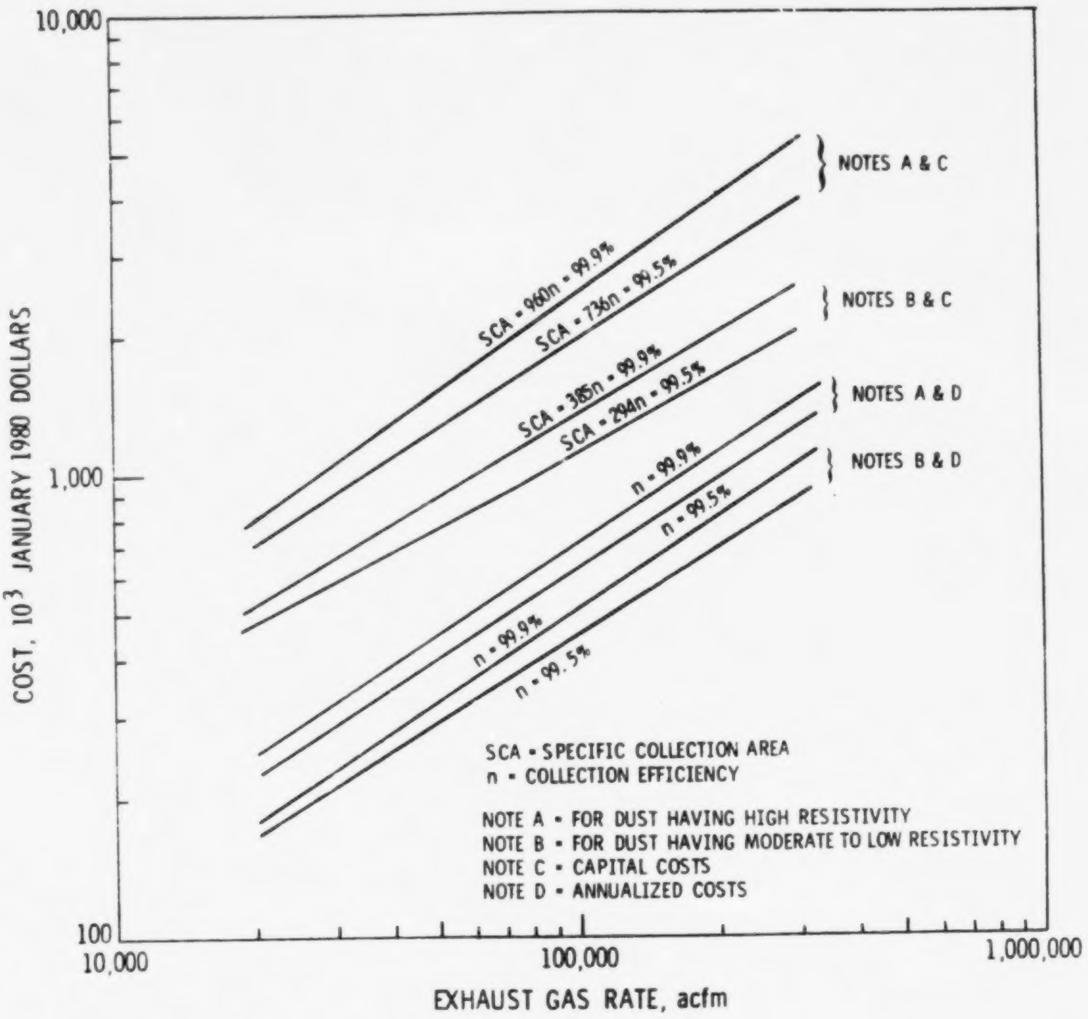

Figure 6-7. Capital and annualized costs of electrostatic precipitators, carbon steel construction.

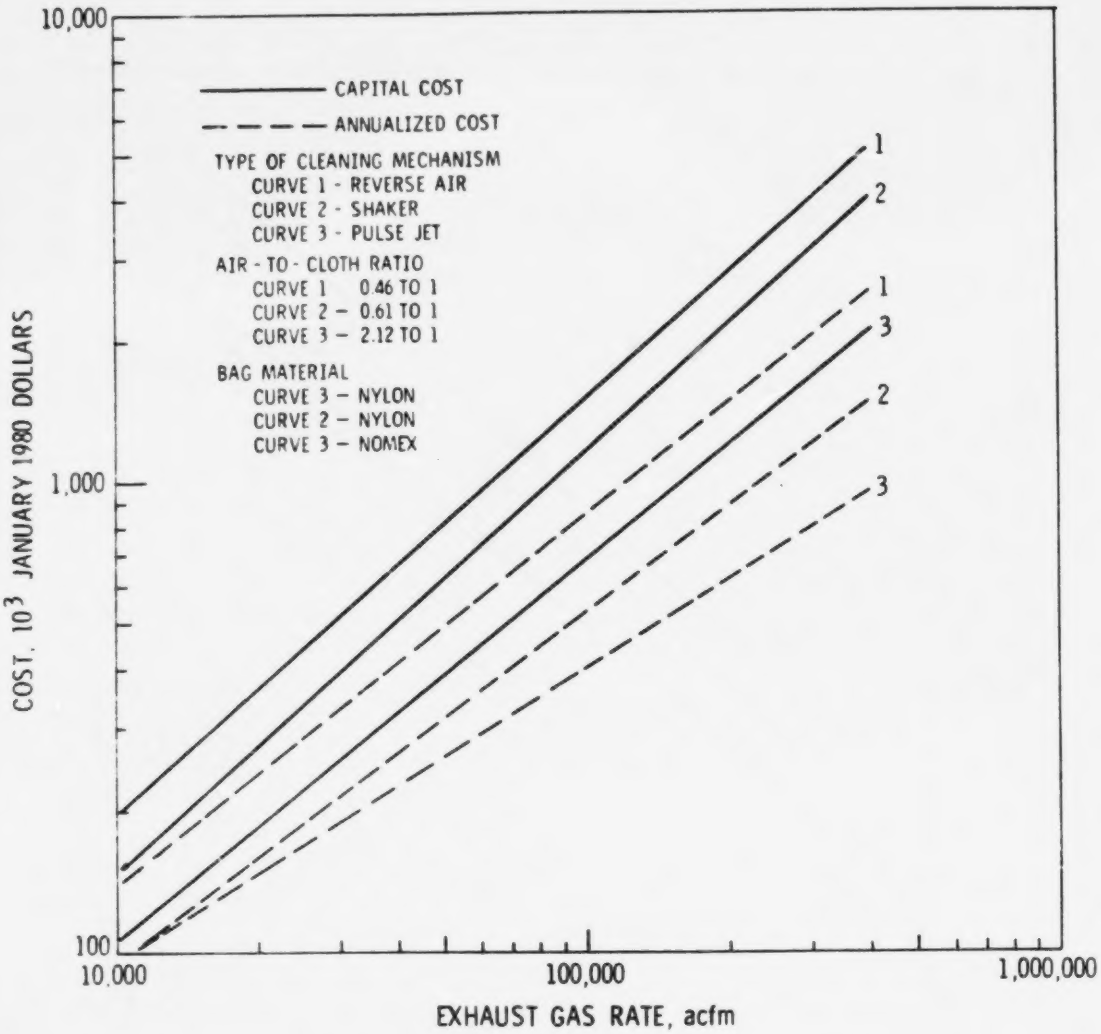

Figure 6-8. Capital and annualized cost of fabric filters, carbon steel construction.

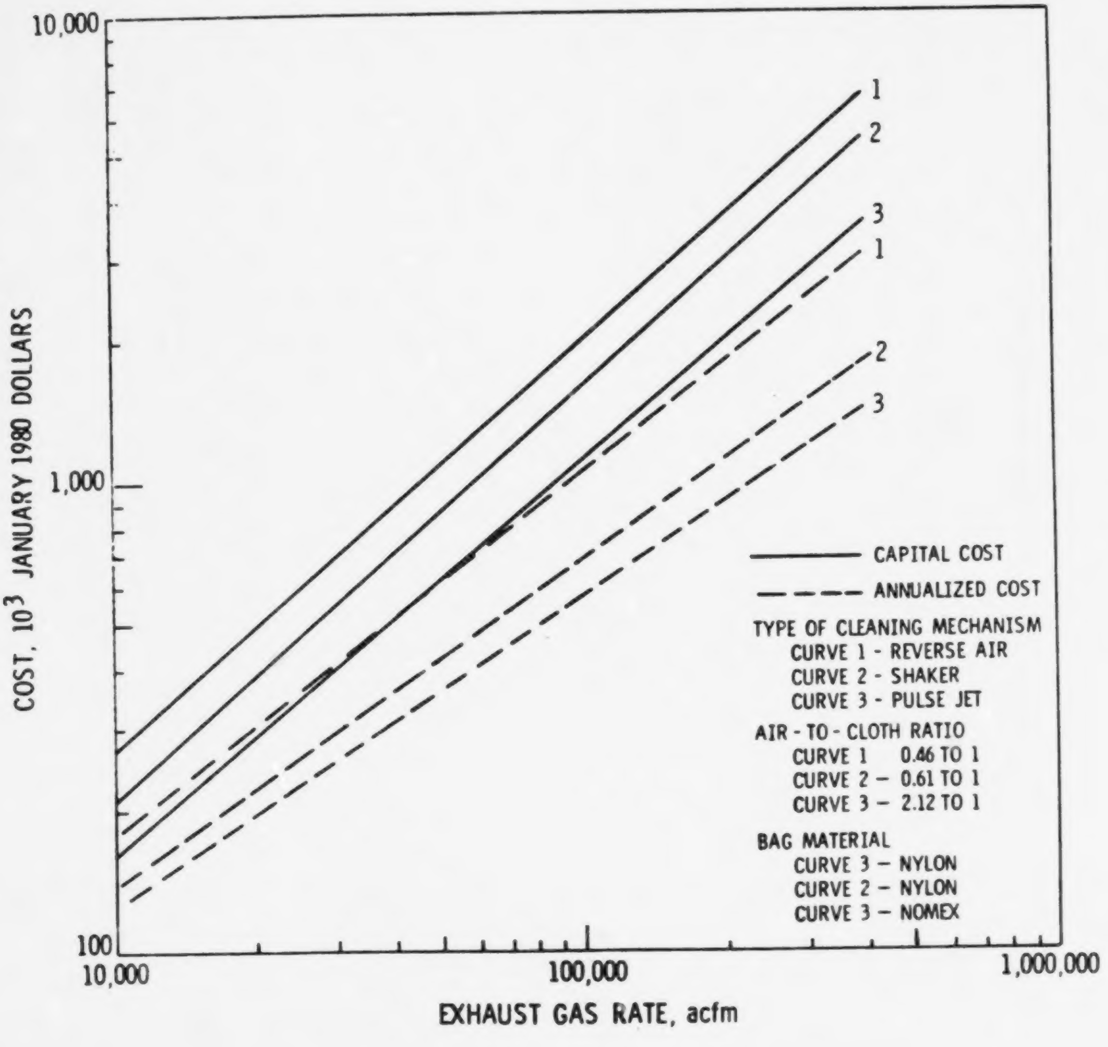

Figure 6-9. Capital and annualized costs of fabric filters, stainless steel construction.

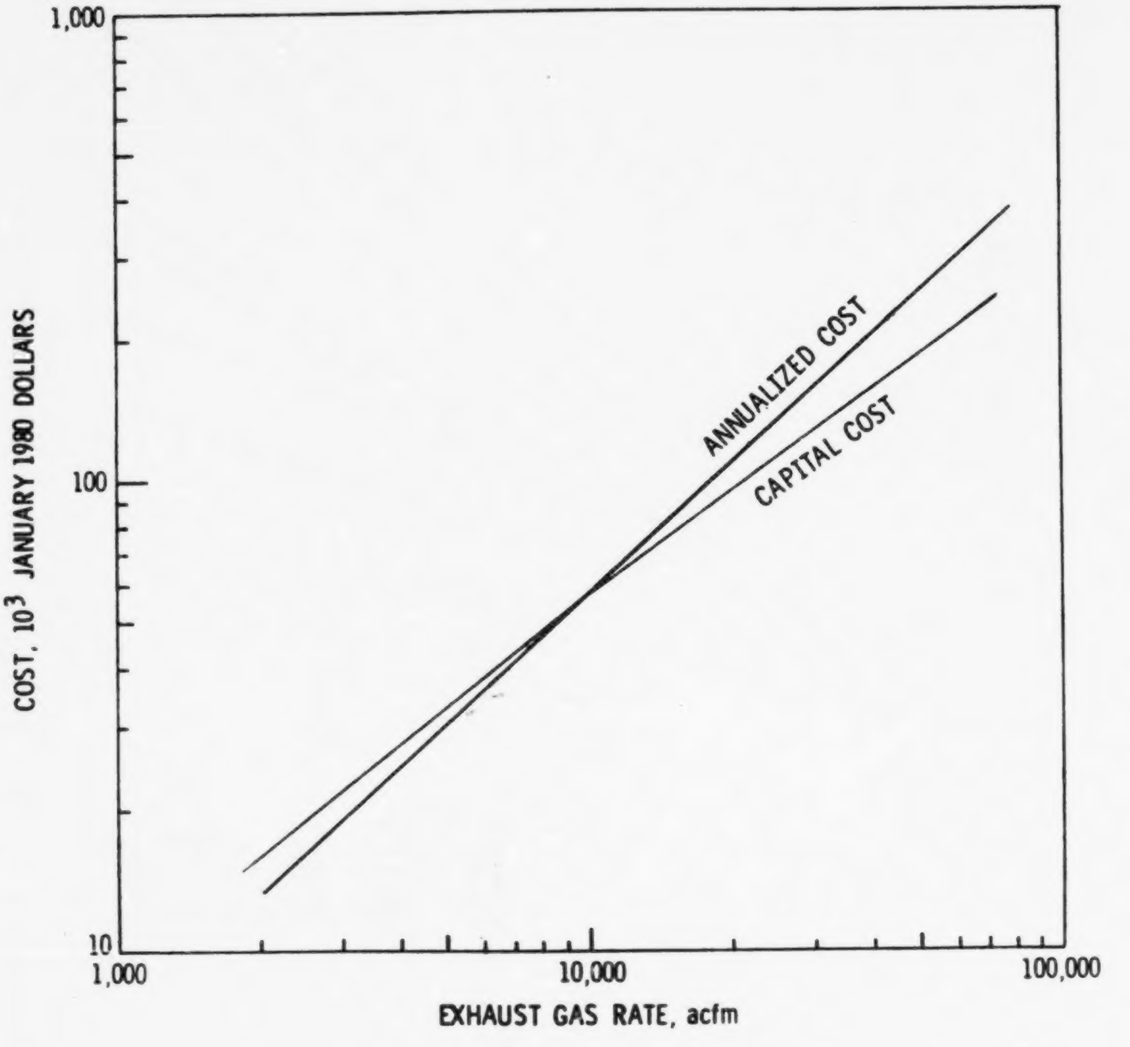

Figure 6-10. Capital and annualized cost of mechanical collectors, carbon steel construction.

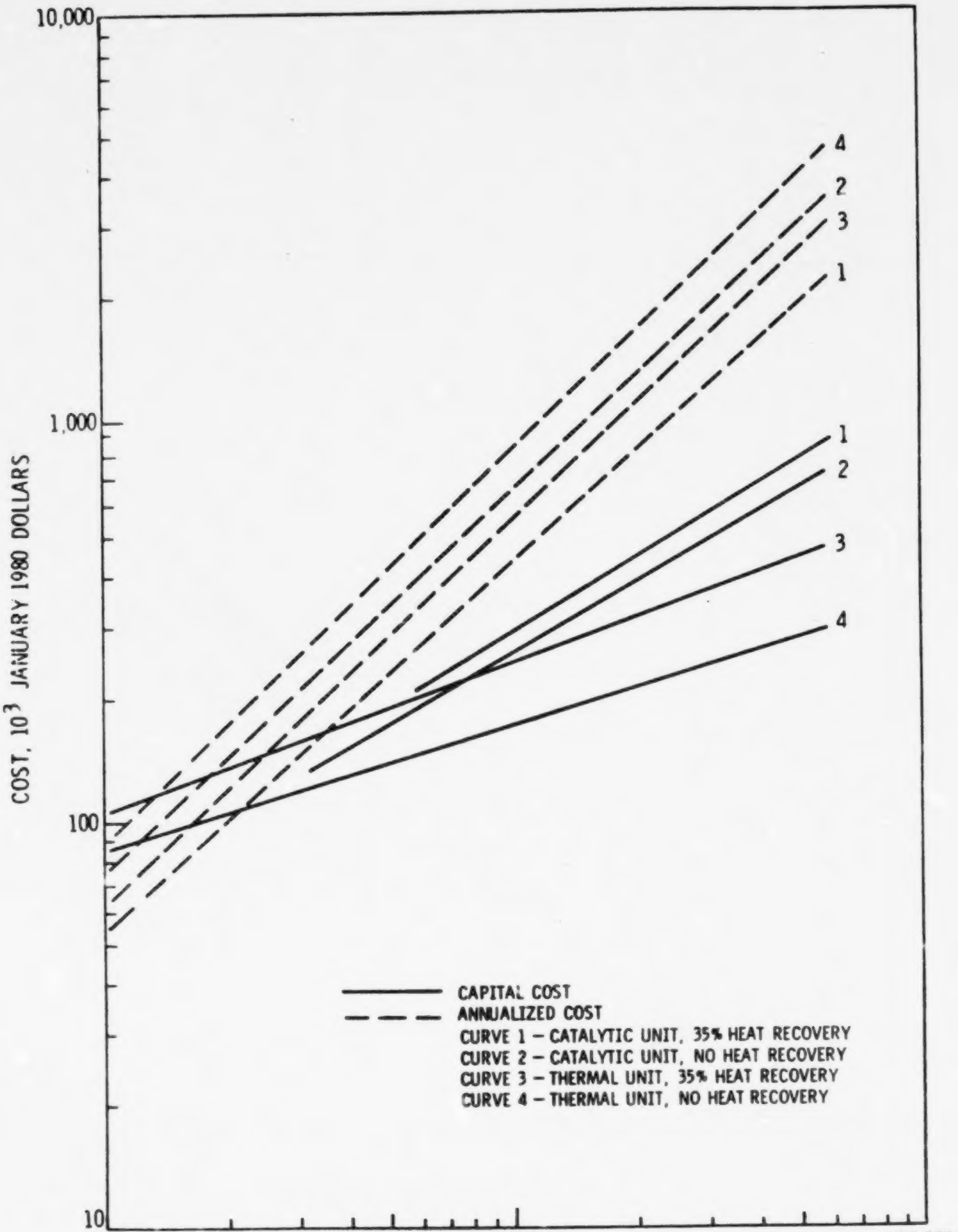

Figure 6-11. Capital and annualized costs of fume incinerators.

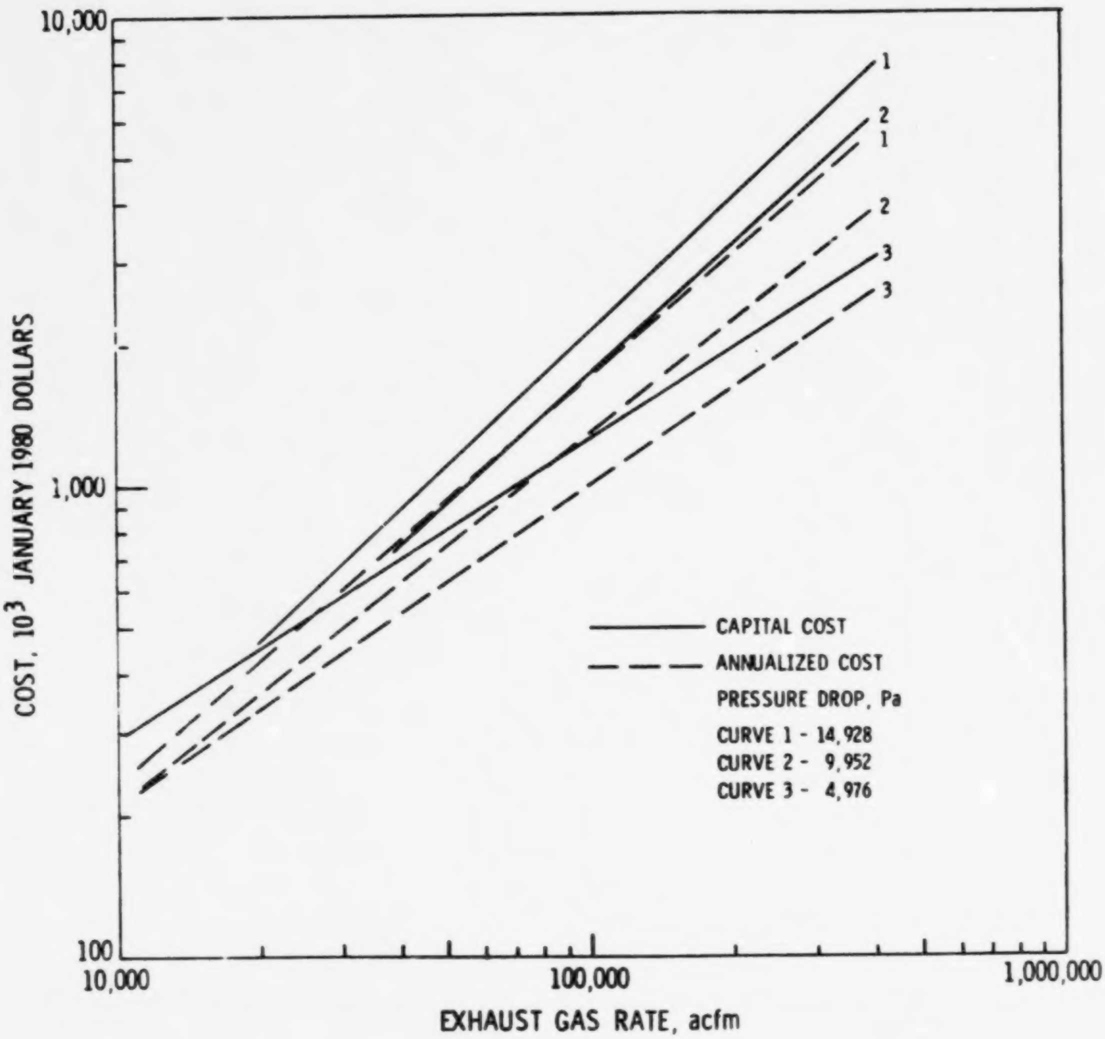

Figure 6-12. Capital and annualized costs of venturi scrubbers, stainless steel construction.

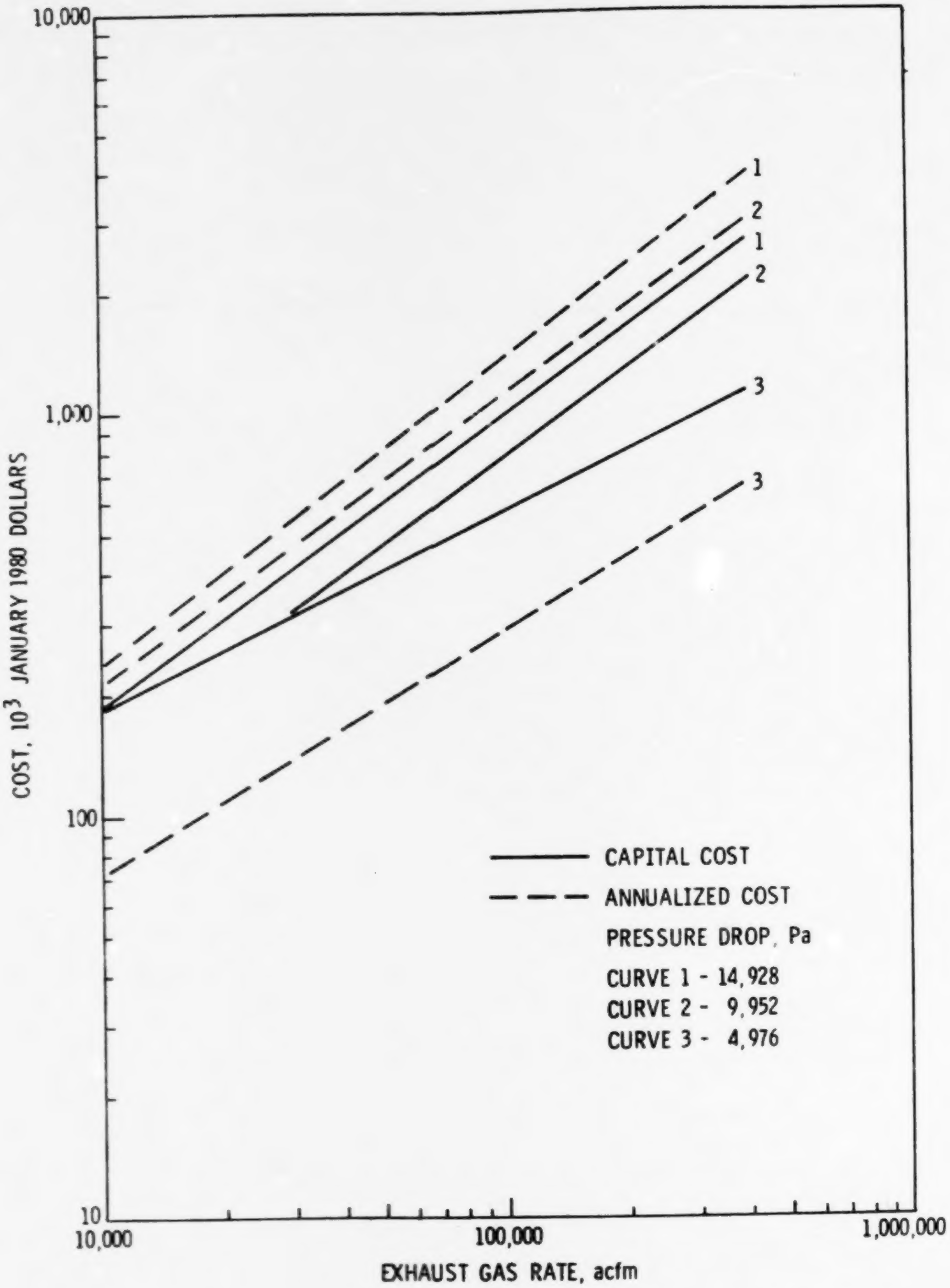

Figure 6-13. Capital and annualized cost of venturi scrubber, carbon steel construction.

bag-cleaning mechanism. The cost curves assume that the fan and drive are process equipment. The control costs include tie-in ductwork, a dust handling conveyor, and a dust storage bin. The costs of thermal insulation and heaters (necessary to prevent condensation in some applications) are not reflected in the cost curves. Separate curves are presented for stainless construction.

6.3.2.4 Mechanical Collectors--

Capital and annualized cost curves for mechanical collector systems are shown in Figure 6-10. System costs include hooding to capture the exhaust at the emission point, ducting, a fan and drive, and a dust storage bin. The system cost is based on carbon steel construction. Collection efficiency for this type of system generally ranges from 80 to 90 percent, depending on the particle size distribution and inlet grain loading.

6.3.2.5 Fume Incinerators--

Fume incinerators are included in this handbook because it is believed that they are sometimes used to cofire hazardous combustible liquid waste as a fuel supplement. Fume incinerators are of two basic types, thermal[a] and catalytic. Although thermal incinerators are less costly from a capital cost standpoint, the fuel savings associated with catalytic units make them attractive for compatible exhaust streams. Both types of units may recover heat and thereby reduce the fuel requirements. The additional cost of the heat exchangers must be compared with the fuel savings on a case-by-case basis. Additionally, the use of catalytic incinerators for control of particulate matter is limited to substances that will not blind or poison the catalytic mesh. Figure 6-11 presents cost curves for both types of units, based on an exhaust stream at 25 percent of the lower explosive limit (LEL). The costs of units having a heat exchanger are based on a 35 percent heat recovery rate. Exhaust streams that are amenable to incineration are normally exhausted to the atmosphere. Thus for purposes of the cost curves presented herein, the fan and drive are considered process equipment. The cost curves include the cost of ductwork to tie the incinerator into the process vent system.

6.3.2.6 Venturi Scrubbers--

Venturi scrubber use ranges from control of small process fugitive exhaust streams to control of high-volume point sources such as basic oxygen furnaces. Figures 6-12 and 6-13 present cost curves for a variety of pressure drops. The costs include a clarifier and circulating pump for the scrubber liquor, a fan and drive, and ductwork sufficient to tie the scrubber into the process exhaust stream.

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[a] Note: Direct-fired incinerators are considered as thermal incinerators for purposes of this analysis.

6.3.2.7 Example Calculation--
The following example is presented to illustrate the use of the cost curves presented in this chapter.

Example: (a) Determine the capital and operating costs of a rotary kiln incineration system with a high energy venturi scrubber having a throughput of 10 million Btu/hour, processing a waste with a heating value of 5000 Btu/pound, and operating with 20% excess air. Assume no heat recovery,
b) Determine the differences in capital and operating costs which might be expected if an electrostatic precipitator were used instead of the high-energy venturi scrubber to collect high resistivity dust with 99.5% efficiency.

a) Using Figure 6-1 the 1980 capital cost of the rotary kiln incineration system with a 10 million Btu/hour throughput is estimated to be 3.5 million dollars. Using Figure 6-3 the 1980 operating cost of this type of system is estimated to be 1,500,000 dollars per year.

b) First, the exhaust gas rate needs to be determined.

From the relationship given on page 6-11,

$$\frac{\text{scf of SA}}{\text{lb of feed}} = \frac{\text{H.V.}}{100} = \frac{5000}{100}\ \text{Btu/lb} = 50\ \frac{\text{scf SA}}{\text{lb/feed}}$$

Assume stack gas temperature = 2000°F or 2460°R

$$\text{acf} = \frac{\text{scf (T °R)}}{492\text{°R}} = \frac{50(2460)}{492} = 250$$

at 20% excess air

$$\text{acf} = 1.20 \times 250 = 300\ \text{acf/lb of feed}$$

Therefore the exhaust gas rate is

$$\text{acfm} = 10\bar{\text{M}}\ \frac{\text{Btu}}{\text{hr}} \times \frac{1\ \text{hr}}{60\ \text{min}} \times \frac{1\ \text{lb}}{5000\ \text{Btu}} \times 300\ \frac{\text{acf}}{\text{lb}}$$

exhaust gas rate = 10000 acfm

For a carbon steel venturi scrubber with an exhaust gas rate of 10,000 actual cfm at a 5 kPa pressure drop, Figure 6-13 shows a capital cost of 185,000 dollars for a carbon steel unit, and its annual operating cost is 72,000 dollars.

For a carbon steel electrostatic precipitator to handle 10,000 actual cfm, Figure 6-7 shows a capital cost of 450,000 dollars and an operating cost of 140,000 dollars.

The change from a venturi scrubber to an electrostatic precipitator would, therefore, be estimated to result in an increased capital cost of 265,000 dollars and an operating cost of 68,000 dollars per year.

6.4 COST EFFECTS OF HAZARDOUS WASTE INCINERATION FACILITY MODIFICATIONS

The purpose of this section is to provide the user with the costs associated with facility modifications. Co[illegible]esented herein are based on the prime operating parameter of the facility component relative to the component's cost.

6.4.1 Cost Effects on Material of Construction

Table 6-2 provides material cost factors which permit determination of a modification cost where materials of construction have been changed. While carbon steel is a widely used construction material, higher alloys are often required. The cost of a new material may be determined using the cost of the original material and factoring up or down using the material cost factors.

TABLE 6-2. MATERIAL COST FACTORS [6]

Construction material	Material factor
Carbon steel	1.0
FRP	0.95
304 Stainless steel	1.55
316 Stainless steel	1.85
Hastelloy C	5.90
Kynar lined FRP	1.55
Teflon lined steel	2.95
Carbon lined steel	4.05
Rubber lined steel	2.30
PVC	1.38
Carpenter 20	4.0 (est.)

6.4.2 Cost Effects Using Euipment Modules

Equipment modifications needed to fit the conditions for a specific incinerator or a specific waste can vary greatly. Reference 7 provides the installed costs of commonly used equipment modules. Where modifications change the capacity of a module, the cost of the modifications can be determined by the difference in installed costs at the two capacities. Figures 6-14a through 6-14c are provided for selected incineration modules.

6.5 TRIAL BURNS

A trial burn is defined as any attempt to incinerate the waste in question for a limited period, and it is designed to establish the conditions at which incineration of waste in a given facility must be carried out to assure protection to public health and the environment. A trial burn may be requested when the EPA believes (1) the information is insufficient to assure protection to public health and the environment, and (2) a trial burn can provide information necessary to assure such protection (i.e., to verify 99.99% destruction

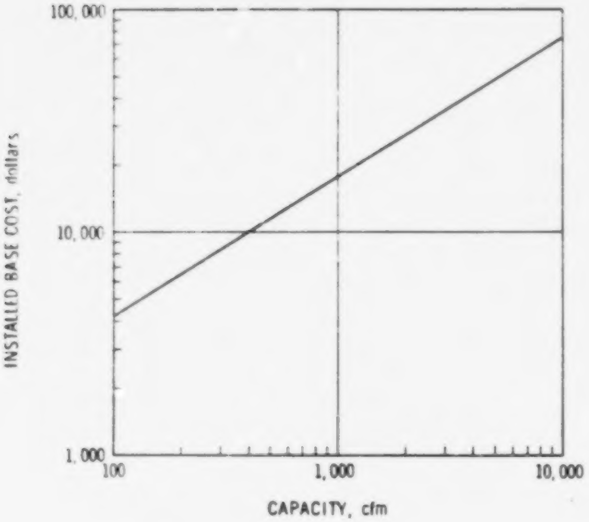

Figure 6-14a. Capacity vs. installed cost for a fan [7[a]].

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[a] Updated using Marshall and Stevens process machinery indexes for 1972 and 1980.

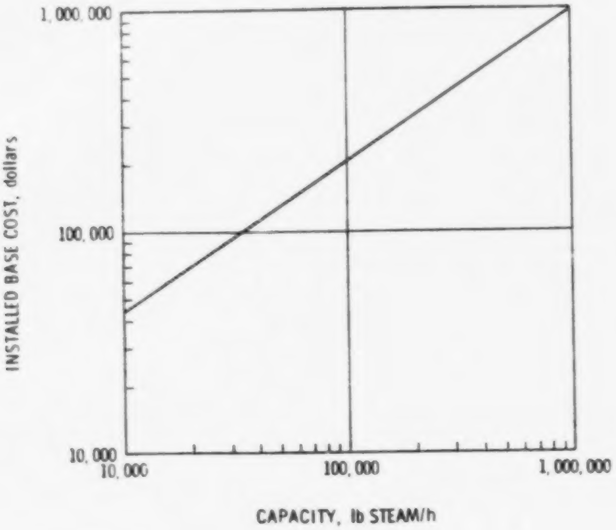

Figure 6-14b. Capacity vs. installed cost for a steam boiler [7[a]].

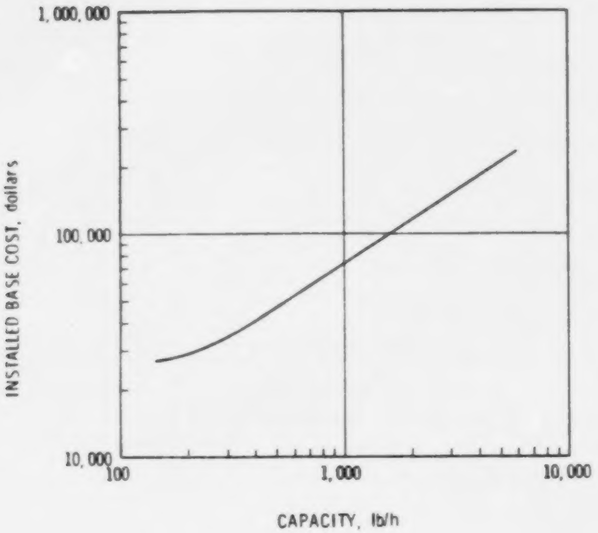

Figure 6-14c. Capacity vs. installed cost for an incinerator [7[a]].

efficiency). A trial burn may comprise either a single burn or a sequence of burns conducted at constant or varied incineration parameters.

A trial burn will be typically conducted at a given facility which is applying for a permit to incinerate the waste in question on a more permanent schedule. The facility could be a commercial (full-sized) incinerator, a pilot-scale unit operated by an incinerator vendor, or a pilot-scale unit operated by a vendor specializing in trial burns.

A trial burn requires a temporary permit from the EPA and may be conducted in the presence of an EPA official. A trial burn itself should not present any serious threat to public or operators' health and the environment. To prevent any serious hazard to public and operators' health and the environment, a trial burn should provide for (a) rapid detection in the incinerator effluents of hazardous materials in quantities potentially threatening health and safety of the public and/or the operators, and (b) rapid incinerator shutdown upon detection of such quantities.

Table 6-3 presents estimated average costs for various of the trial burn activity. Costs contained in Table 6-3 are for trial burns at an existing, full-scale incinerator. It is assumed that the incinerator is already permitted to burn hazardous wastes and that the trial burn is being conducted for the plant to obtain a permit to burn an additional hazardous waste. These

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[a] Updated using Marshall and Stevens process machinery indexes for 1972 and 1980.

TABLE 6-3. TRIAL BURN COST COMPONENTS (DOLLARS)[a,b]

	Average	Range
Site survey	200[c]	$ 100 - 500
Equipment preparation	1,000[c]	500 - 2,000
Equipment setup and takedown	1,000[c]	500 - 2,000
Stack sampling	1,000[d]	500 - 2,000
Sample analysis	3,000[d]	1,000 - 5,000
Equipment cleanup	500[c]	300 - 800
Report preparation	1,000[c]	500 - 3,000

[a] Costs included in this table are estimated averages obtained by questioning selected consultants experienced in trial burn situations. Additional costs may be incurred under specific conditions.

[b] Mid-1980 estimated costs.

[c] One-time costs.

[d] Costs during trial burn period. (Dollars per day of testing.)

costs are based principally on information furnished by privately-owned environmental laboratory and consulting firms. The trial burn period is assumed to require a minimum of 4 hours but may extend to several days or weeks, depending upon facility operations and management decisions concerning the number of replicative samples to be taken. Facility operators may choose to conduct parallel tests or implement procedures for permit applications simultaneous with conducting trial burns. Any costs incurred through normal operations and those related to obtaining a permit under Subtitle C of RCRA are not included in the trial burn activity costs.

Specific situations could arise which would increase costs above those represented in Table 6-3. These include costs for incinerating new and unfamiliar wastes, new construction, and retrofitting of existing facilities.

6.5.1 Normal Operations

Previously constructed and existing commercial-sized facilities are assumed, with normal operating costs (fixed and variable) expected to be recovered through established charges for incinerating customers' wastes. These costs include amortized engineering design and capital investment costs, costs for analyzing incoming wastes, burn adjustments, supplementary fuel, and expenditures associated with installing and operating pollution control devices. Wastes for the trial burns and related storage facilities, including use of supplementary fuel, are assumed as part of the facilities normal operations for which the usual charges offset operating costs. All costs related to obtaining a permit under Subtitle C of RCRA are excluded from consideration as trial burn costs.

6.5.2 Trial Burn Activities

6.5.2.1 Site Survey--
Costs include professional services and travel to a local site for inspection of the facility to be tested and discussion of plans for trial burns. Specific characteristics of wastes to be incinerated are assumed known or provided by waste generators and listed on manifest records or analyzed previously. Information on the compatibility of these wastes with the specific facility characteristics is assumed available.

6.5.2.2 Equipment Preparation--
Sampling equipment may be leased by the facility or provided by a consulting firm. Certain costs are incurred in calibrating and loading of instruments and transport to facility site; estimates of these average costs are shown in Table 6-3.

6.5.2.3 Equipment Setup and Takedown--
Installation of equipment includes any scaffolding and securing of ports and proper sampling instruments at facility stack(s) to ensure the necessary monitoring and procurement of trial burn samples.

6.5.2.4 Stack Sampling--
A minimum of three tests involving 1 to 1 1/2 hours per test is assumed. Costs for testing, instrumentation, and adjustments associated with a permit application are considered separate costs not attributable to the trial burn activity. Development of sampling procedures and verification of test methods are presumed available and accomplished prior to the trial burns.

6.5.2.5 Sample Analysis--
Laboratory analysis costs include preservation and transporting of samples to an off-site laboratory and makeup of fractional samples. Compounds to be analyzed include those potential air pollutants listed in the previous section (Table 5-13). GCMS testing is conducted for the chlorinated hydrocarbons and EPA test methods Nos. 5, 6, and 7 for various other potential pollutants, including particulate matter. GCMS testing at the site is excluded.

Daily testing assumes one EPA Method No. 5, two Method No. 6, and four Method No. 7 tests for analyzing single waste trial burns. Blending of incoming wastes could complicate analytical procedures and increase the laboratory analysis costs.

6.5.2.6 Equipment Cleanup--
These costs are the routine costs incurred for cleaning and storing various sampling and analysis equipment.

6.5.2.7 Report Preparation--
The written report displays and interprets the trial burn results. Preparation of this report and the information contained therein is considered independent from any information produced for permit negotiations.

6.6 REFERENCES

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APPENDIX B

GLOSSARY

This appendix is a glossary of terms used throughout this Handbook.

activation energy: The quantity of heat needed to destabilize molecular bonds and form reactive intermediates so that the reaction will proceed

afterburner (or combustor): A pollution control device that uses combustion to reduce the emission levels of organic gaseous and particulate matter.

ambient concentration (ac): The appropriately time-averaged concentration of a substance at a location to which the general public has access.

analyzer: A device used to monitor emissions, such as: (1) a nondispersive infrared analyzer (monitors SO_2, NO_x, CO, CO_2, and other gases that absorb light in the infrared region of the spectrum, including hydrocarbons), (2) a nondispersive ultraviolet analyzer (monitors gases that absorb light in the ultraviolet and visible regions of the spectrum), (3) a polarographic analyzer (monitors SO_2, NO_2, CO, O_2, and H_2S), (4) an electrocatalytic oxygen analyzer, and (5) a paramagnetic oxygen analyzer.

angle of repose: The angle at which matter will lie or stack in a stationary configuration.

ANSI: American National Standards Institute.

APCD: Air pollution control device.

ash: The solid residue that remains after a material is incinerated. There are two types: (1) bottom ash remains in the combustion chamber after incineration, and (2) fly ash is entrained in exhaust gases leaving the incinerator.

ash fusion temperature (or melting temperature of ash): The temperature at which ash has the potential to melt.

ASME: American Society of Mechanical Engineers.

baghouse: An air pollution abatement device used to trap particulates by filtering gas streams through large fabric bags.

BaP: benzo(a)pyrene.

beta attenuation monitor: An instrument that measures the absorption of β-radiation as it traverses a small area onto which aerosol particles are collected by means of inertial impaction.

blowdown: The portion of scrubbing fluid that is purged in order to prevent buildup of dissolved solids.

BOD: Biological oxygen demand.

catalytic combustion: A type of combustion employing a catalyst bed.

coburning: The burning of waste and a fuel.

coincineration: The joint incineration of hazardous waste and refuse and/or sludge.

combustor (or afterburner): A pollution control device that uses combustion to reduce the emission levels of organic gaseous and particulate matter.

dedicated incinerator: A privately owned incinerator used to burn only the owner's wastes.

deflagration: The act of burning very suddenly and violently, but without a resultant shock wave (detonation).

destruction and removal efficiency (DRE): This term is defined by the following equation:

$$DRE = \frac{W_{in} - W_{out}}{W_{in}} \times 100\%$$

where:

DRE = Destruction and removal efficiency
W_{in} = Mass feed rate of principal organic hazardous constituent(s) in the waste stream feeding the incinerator (kg/min)
W_{out} = Mass emission rate of principal organic hazardous constituent(s) present in exhaust emissions (kg/min) [downstream of all air pollution control equipment].

destruction efficiency (DE): Same as destruction and removal efficiency except W_{out} = mass emission rate of principal organic hazardous constituent(s) leaving combustion zone of incinerator (upstream of all air pollution control equipment).

dry sorption process: A process that involves contacting the gas stream with a solid phase that can remove one or more of the gaseous contaminants.

dwell time: See residence time.

effluent: A discharge of pollutants (either gases, liquids, or solids) into the environment.

electrostatically augmented scrubbers: Control devices that couple the mechanisms of electrostatic attraction and inertial separation by charging particles prior to entry into a wet collector.

electrostatic precipitator (ESP): An air pollution control device that removes particulate matter by imparting an electrical charge to particles in a gas stream, causing their collection on an electrode.

excess air: The air flow rate above that required to achieve theoretically complete combustion.

fabric filter: A device for removing dust and particulate matter from industrial emissions by filtration through cloth or other porous materials.

flash point: The lowest temperature at which a material will volatilize to yield sufficient vapor to form a flammable gaseous mixture with air.

flooding velocity: The gas velocity or narrow range of gas velocities in a packed bed or plate tower scrubber at which (for a given packing or plate design and liquid flow rate) the liquid flow down the column is impeded, and a liquid layer is formed at the tip of the column. Eventually, liquid is blown out the top of the column.

fluid: Any substance (for example, a liquid or slurry) that tends to flow or conform to the outline of its container.

fluidized bed incinerator: An incinerator consisting of a refractory-lined vessel containing inert granular material through which gases are blown at a rate sufficiently high to cause the bed to expand and act as a theoretical fluid. The gases are injected through nozzles that permit upward flow the bed but restrict downward flow of the material.

fugitive emissions: Pollutants arising from sources other than stacks and effluent pipes.

GC: Gas chromatograph

general purpose incinerator: An incinerator that burns miscellaneous types of wastes, usually from numerous sources and customers.

HCB: Hexachlorobenzene

heating value: The quantity of heat released when waste is burned, commonly expressed as Btu/lb. The higher heating value includes the heat of condensation of the water present in the waste and the heat formed in the combustion reaction; the lower heating value represents the heat formed in the combustion reaction; and the net heating value is the lower heating value minus the energy necessary to vaporize any moisture present.

heat of combustion: The heat evolved from the union of combustible elements with oxygen.

hygroscopicity: Act of attracting moisture from the air.

incinerator: An engineered apparatus used to burn waste substances in which all the combustion factors (temperature, retention time, turbulence, and combustion air) can be controlled.

incinerator, similar: Incinerator A is similar to incinerator B if, based on the best engineering judgement, while incinerating identical waste as incinerator B, the stream leaving the combustion chamber of incinerator A contains equal or lower amounts of each, but no additional, potentially hazardous components as the stream leaving the combustion chamber of incinerator B.

kinematic viscosity: The ratio of absolute viscosity to density.

liquid injection incinerator: An incinerator that uses an atomization device or nozzle to feed liquid waste.

mass spectrometer: An instrument that analyzes samples by sorting molecular or atomic ions according to their masses and electrical charges.

MEG: See multimedia environmental goals.

microwave plasma destruction (or plasma destruction): A method of destruction that uses microwave energy to excite the molecules of a carrier gas (such as helium or air), thus raising electron energy levels and forming highly reactive free radicals.

mist eliminator: A control device used to reduce emissions of liquid droplets, usually from scrubbers. There are three types: (1) cyclone mist eliminators (2) fiber bed mist eliminators and (3) wire mesh eliminators.

molten salt incinerator: An incinerator in which waste is injected below the surface of a molten salt bath.

multimedia environmental goals (MEG's): The levels of contaminants (in ambient air, water, or land, or in emissions or effluents conveyed to ambient media) that (1) will not produce negative effects in the surrounding populations or ecosystems, or (2) represent control limits demonstrated to be achievable through technology.

multiple chamber incinerator: An incinerator in which wastes are thermally decomposed in the presence of oxygen in the primary chamber, and decomposition products are oxidized in the secondary chamber(s).

multiple hearth incinerator: An incinerator containing multiple refractory-lined hearths, vertically aligned, designed for staged drying and combustion of wastes.

NFPA: National Fire Protection Association.

nitrogen oxides (NO_x): The collective term used for the gaseous oxides of nitrogen, primarily nitric oxide (NO) and nitrogen dioxide (NO_2).

NPDES: National pollutant discharge elimination system.

packed tower: An air pollution control device in which polluted air is forced upward through a tower packed with materials (such as raschig rings, ceramic saddles, tiles, marbles, crushed rock, or wood chips) while a liquid is sprayed downward on the packing material. The pollutants in the air stream dissolve and/or chemically react with the liquid.

PAH: Polycyclic aromatic hydrocarbons

particulates: Minute solid or liquid particles in the air or in an emission. Particulates include dust, smoke, fumes, mist, spray and fog.

PCB: Polychlorinated biphenyls.

piezoelectric monitor: A type of particle monitor which measures mass concentration by utilization of a vibrating piezoelectric crystal driven by a standard oscillation circuit.

PNA: Polynuclear aromatic compounds.

POHC: Principal organic hazardous constituent.

POM: Polycyclic organic matter.

pyrolysis: The thermal decomposition of a compound in the absence of oxygen.

pyrophoric: Capable of igniting spontaneously.

quench: To cool rapidly.

removal efficiency: The ratio of the mass rate of flow of the contaminants going into a control device minus the mass rate of the contaminants going out of the control device to the mass rate of flow of the contaminants going into the control device.

residence time: The period of time that the waste is exposed to the reported temperature in the incinerator.

retention time: See residence time.

rotary kiln incinerator: An incinerator with a cylindrical, horizontal, refractory-lined shell that is mounted at a slight incline. Rotation of the shell causes mixing of the waste with the combustion air.

scrubber: An air pollution control device that uses a liquid to remove pollutants from a gas stream by absorption and/or chemical reaction. (Scrubbers also reduce the temperature of the emission.)

similar waste: Waste A is similar to waste B if, based on best engineering judgement, the incineration of waste A in the same facility and under the same operating conditions as those used for waste B would yield a stream leaving the combustion chamber that contains equal or lower amounts of each, (but no additional) potentially hazardous pollutants compared to the amounts yielded by waste B incineration.

sludge: A nonpumpable mixture of solids and liquids.

slurry: A pumpable mixture of solids and liquids.

solifluction: Liquid seepage.

SSU (standard saybolt universal): A unit for measuring kinematic viscosity.

starved air combustion (or thermal gasification): A process that utilizes equipment and process flows similar to those for incineration; but, in this process, less than the theoretical amount of air for complete combustion is supplied.

TCDD: Tetrachlorodibenzo-p-dioxin.

TDAS: Thermal decomposition analytical system.

TDD: Thermal decomposition device

TDI: Toluene diisocyanate.

temperature: A measure of the level of thermal energy in molecules to which a waste is exposed during the incineration process.

TLV (threshold limit value): Exposure levels representing conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effects. For airborne substances, the exposure levels are stated as airborne concentrations and durations of exposure, including:

- Time-weighted average concentrations for a normal 8-hour workday or 40-hour workweek (threshold limit value - time-weighted average).
- Maximal concentrations to which workers can be exposed for a period up to 15 minutes (threshold limit value - short-term exposure limit).
- Concentrations that should not be exceeded even instantaneously (threshold limit value - ceiling).

These values are published annually by the American Conference of Governmental Industrial Hygienists.

TOD: Total oxygen demand.

trial burn: Any attempt to incinerate the waste in question for a limited period. A trial burn is designated to establish the conditions at which incineration of waste in a given facility must be carried out to assure protection to public health and environment.

trial burn proposal: A detailed plan which describes the procedure that will be used and the precautions that will be taken during a trial burn.

turndown ratio: Maximum to minimum operating range of a parameter.

UDRI: University of Dayton Research Institute.

viscosity: The property of a fluid or semifluid that enables it to develop and maintain an amount of shearing stress (dependent upon the velocity of flow) and then to offer continued resistance to flow.

volatile organic compounds: Organic compounds that are readily vaporized at a relatively low temperature.

WG: Water gage.

wet air oxidation: A process that operates on the principle that the rate of oxidation of organic compounds is increased at high pressures. By pressurizing an aqueous organic waste, heating it to an appropriate temperature, and then introducing atmospheric oxygen, liquid-phase oxidation reaction is produced, destroying most of the organics.

wet electrostatic precipitator (WEP): An electrostatic precipitator which achieves particle collection by the introduction of liquid droplets to the gas stream through sprayers located above the electrostatic field section of the precipitator.

wet scrubber: An air pollution control device used to remove pollution by bringing a polluted gas stream into contact with a liquid.

TABLE C-1. CONVERSION FACTORS

To convert from	To	Multiply by
acre	square kilometer (km^2)	0.00404047
	square meter (m^2)	4,046.86
	square mile (mi^2)	0.0015625
Btu (British thermal unit)	calorie (cal)	251.99576
	joule (J)	1,054.35
	kilocalorie (kcal)	0.251996
Btu/minute (Btu/min)	joule/second (J/s)	17.5725
Btu/pound (Btu/lb)	calorie/gram (cal/g)	0.555555
Btu/(pound·°F)[Btu/(lb·°F)]	calorie/(gram·°C) [cal/(g·°C)]	1.0
Btu/second (Btu/s)	Kilocalorie/hour (kcal/h)	970.185
	kilocalorie/minute	15.1197
calorie (cal)	Btu	0.0039683207
	kilocalorie (kcal)	0.001
	joule (J)	4.184
calorie/gram (cal/g)	Btu/pound (Btu/lb)	1.8
calorie/hour (cal/h)	Btu/hour (Btu/h)	0.0039683207
	erg/second (erg/s)	11,622.222
centigrade (°C)	Fahrenheit (°F)	°F = (1.8 x °C) +32
	Kelvin (°K)	°K = °C + 273.17
centimeter (cm)	inch (in.)	0.39370079
centipoise (cP)	gram/(centimeter·second) [g/(cm·s)]	0.01
centistokes (cSt)	saybolt seconds (SSU)	See Table C-2
cubic centimeter (cm^3)	cubic foot (ft^3)	3.5314667 x 10^{-5}
	cubic inch (in.^{3})	0.061023744
	cubic yard (yd^3)	1.3079506 x 10^{-6}
cubic foot (ft^3)	cubic centimeter (cm^3)	28,316 847
	cubic meter (m^3)	0.028316847
	gallon (U.S. liquid)	7.4805195
	liter (L)	28.316847
cubic meter (m^3)	cubic foot (ft^3)	35.314667
	cubic yard (yd^3)	1.3079506
	liter (L)	1,000
dyne/square centimeter (dyne/cm^2)	atmosphere (atm)	9.86923 x 10^{-7}
	bar	1 x 10^{6}
	centimeter of mercury @ 0°C (cm Hg @ 0°C)	7.50062 x 10^{-5}
	centimeter of water @ 4°C (cm H$_2$O @ 4°C)	0.00109745
	inch of mercury @ 32°F (in. Hg @ 32°F)	2.95300 x 10^{-5}
	inch of water @ 4°C (in. H$_2$O @ 4°C)	0.000401474
	pascal (Pa)	0.1
	pound/square inch (lb/in.^{2})	1.450377 x 10^{-5}
Fahrenheit (°F)	Centigrade (°C)	°C = 0.5556 (°F - 32°)
	Rankin (°R)	°R = °F + 459.7°
foot (ft)	centimeter (cm)	30.48
	inch (in.)	12
	meter (m)	0.3048
	millimeter (mm)	304.8

(continued)

TABLE C-1 (continued)

To convert from	To	Multiply by
gallon (U.K. liquid) [gal]	gallon (U.S. liquid) [gal]	1.20095
	liter (L)	0.00668932
gallon (U.S. liquid) [gal]	cubic centimeter (cm^3)	3,785.4118
	cubic foot (ft^3)	0.133680555
	cubic inch ($in.^3$)	231
	cubic meter (m^3)	0.0037854118
	liter (L)	3.7854118
grains/standard cubic foot (gr/scf)	milligrams/standard cubic meter	2288.3
gram (g)	kilogram (kg)	0.001
	pound (lb)	0.0022046226
gram/(centimeter·second)	poise (P)	1
gram/cubic centimeter (g/cm^3)	grain/milliliter (gr/mL)	15.43279
	gram/milliliter (g/mL)	1
	pound/cubic foot (lb/ft^3)	62.427961
	pound/cubic inch ($lb/in.^3$)	0.036127292
	pound/gallon (U.S. liquid) (lb/gal)	8.3454044
gram/cubic meter (g/m^3)	grain/cubic foot (gr/ft^3)	0.43699572
gram/liter (g/L)	part/million (ppm)	1,000
	pound/cubic foot (lb/ft^3)	0.06242621
gram/milliliter (g/mL)	gram/cubic centimeter (g/cm^3)	1
	pound/cubic foot (lb/ft^3)	62.4261
	pound/gallon (U.S.) (lb/gal)	8.345171
inch of water @ 4°C (in H_2O @ 4°C)	atmosphere (atm)	0.0024582
	inch of mercury @ 32°F (in. Hg @ 32°F)	0.0735529
	kilopascal (kPa)	249,082
	pascal (Pa)	249.082
	pound/square inch (psi)	0.03612628
joule (J)	Btu	0.000948451
joule/second (J/s)	Btu/minute (Btu/min)	0.0569071
	Btu/hour (Btu/h)	3.414426
kilocalorie (kcal)	Btu	3.9683207
	erg	4.184×10^1
	joule (J)	4,184
kilogram (kg)	pound (avoirdupois) [lb (avdp)]	2.2046226
	ton (short, 2,000 lb mass)	0.0011023113
liter (L)	cubic foot (ft^3)	0.035314667
	quart (U.S. liquid) (qt)	1.0566882
meter (m)	foot (ft)	3.2808399
	inch (in.)	39.370079
	mile (statute) (mi)	0.00062137119
	millimicrons (mμ)	1×10^9
	yard (yd)	1.0936133
pascal (Pa)	atmosphere (standard) (atm)	9.869233×10^{-6}
	dyne/square centimeter ($dyne/cm^2$)	10
	inch of water @ 39.2°F (in. H_2O @ 39.2°F)	0.004014742
	inch of water @ 60°F (in. H_2O @ 60°F)	0.004018647
	pound-force/square inch ($lb\text{-}force/in.^2$) (psi)	0.0001450377

(continued)

TABLE C-1 (continued)

To convert from	To	Multiply by
pascal·seconds (Pa·s)	Poise	10.00
poise (P)	centipose (cP)	100.00
	dyne·second/square centimeter	1
	gram/(centimeter·second) [g/(cm·s)]	1
	pound/(second·foot) [lb/s·ft]	0.0672
pound (lb)	gram (g)	953.59237
pound/(foot·second) [lb/(ft·s)]	poise (P)	14.88
pound/cubic foot (lb/ft^3)	gram/cubic centimeter (g/cm^3)	0.016018463
	kilogram/cubic meter (kg/m^3)	16.018463
pound/cubic inch (lb/in.^{3})	gram/cubic centimeter (g/cm^3)	27.679905
	gram/liter (g/L)	27.68068
	kilogram/cubic meter (kg/m^3)	27,679.905
pound/gallon (U.K. liquid) [lb/gal]	pound/cubic foot (lb/ft^3)	6.228839
pound/gallon (U.S. liquid) [lb/gal]	gram/cubic centimeter (g/cm^3)	0.11982643
	pound/cubic foot (lb/ft^3)	7.4805195
pound/square inch (psi)	atmosphere (atm)	0.0680460
saybolt seconds (SSU)	centistokes (cSt)	see Table C-2
square foot (ft^2)	acre	2.295684 x 10^{5}
	square centimeter (cm^2)	929.0304
	square inch (in.^{2})	144
	square meter (m^2)	0.09290304
square kilometer (km^2)	acre	247.10538
	square meter (m^2)	1,000,000
	square mile (mi^2)	0.38610216
square meter (m^2)	acre	0.00024710538
	square foot (ft^2)	10.763910
	square kilometer (km^2)	0 000001
stoke (St)	centistoke (cSt)	1 x 10^2
	saybolt seconds (SSU)	See Table C-2
	square centimeter/second (cm^2/s)	1
	square foot/hour (ft^2/h)	3.875
	square foot/second (ft^2/s)	0.001076
ton (metric)	kilogram (kg)	1000.
	ton (short, 2,000 lb mass)	1.1023113

TABLE C-2. KINEMATIC VISCOSITY CONVERSION FACTORS FOR CENTISTOKES TO SSU UNITS[a]

	Saybolt seconds at (SSU)				Saybolt seconds at (SSU)		
Centi-stokes	100°F	130°F	210°F	Centi-stokes	100°F	130°F	210°F
2.0	32.6	32.7	32.8	28.0	132.1	132.4	133.0
3.0	36.0	36.1	36.3	30.0	140.9	141.2	141.9
4.0	39.1	39.2	30.4	32.0	149.7	150.0	150.6
5.0	42.3	42.4	42.6	34.0	158.7	159.0	159.8
6.0	45.5	45.6	45.8	36.0	167.7	168.0	168.9
7.0	48.7	48.8	49.0	38.0	176.7	177.0	177.9
8.0	52.0	52.1	52.4	40.0	185.7	186.0	187.0
9.0	55.4	55.5	55.8	42.0	194.7	195.1	196.1
10.0	58.8	58.9	59.2	44.0	203.8	204.2	205.2
11.0	62.3	62.4	62.7	46.0	213.0	213.4	214.5
12.0	65.9	66.0	66.4	48.0	222.2	222.6	223.8
14.0	73.4	73.5	73.9	50.0	231.4	231.8	233.0
16.0	81.1	81.3	81.7	60.0	277.4	277.9	279.3
18.0	89.2	89.4	89.8	70.0	323.4	324.0	325.7
20.0	97.5	97.7	98.2	80.0	369.6	370.3	372.2
22.0	106.0	106.2	106.7	90.0	415.8	416.6	418.7
24.0	114.6	114.8	115.4	100.0	462.0	462.9	465.2
26.0	123.3	123.5	124.2				

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[a] For kinematic viscosity levels above 100 centistokes, use the same ratio as the ratio in the table above for 100 centistokes (at the temperature of the fluid); e.g., 120 centistokes (@ 130°F) = 120 x 4.629 = 555.5.

To obtain the saybolt universal viscosity at a temperature not shown in te table above, multiply the saybolt universal viscosity @ 100°F by [1 + (t - 100) 0.000064], where "t" is the temperature in degrees fahrenheit, e.g., 10 centistokes @ 220°F = 58.8 x [1 + (220-100) 0.000064]; = 58.8 x 1.00768 = 59.25

APPENDIX D

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APPENDIX E

LABORATORY-SCALE THERMAL DECOMPOSITION ANALYTICAL DATA

1. INTRODUCTION

Laboratory-scale thermal decomposition data for hazardous wastes can be helpful for establishing sampling and analytical protocols for incinerator performance monitoring, and for determining potential operating conditions for incinerator trial burns. Such data can be generated using laboratory-scale thermal decomposition systems such as the Thermal Decomposition Analytical System (TDAS) employed at the U.S Environmental Protection Agency research program at the University of Dayton Research Institute (UDRI). The objectives of this appendix are to describe how the data are collected and to provide guidance for their use.

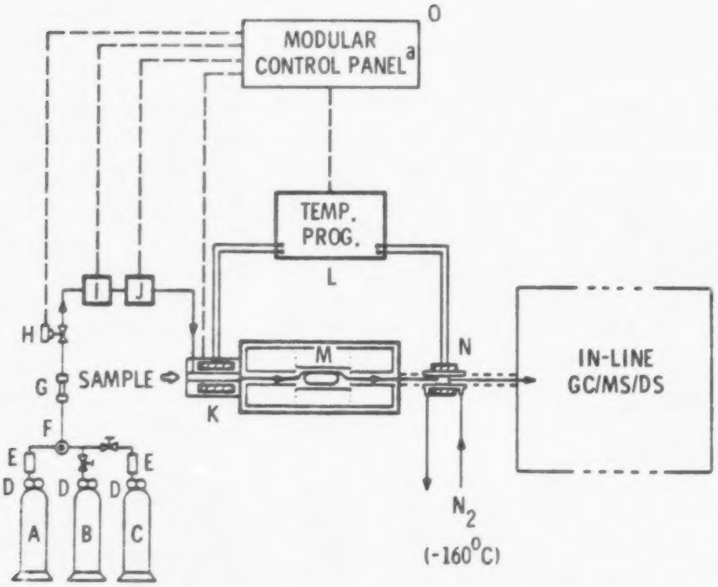
2. THERMAL DECOMPOSITION ANALYTICAL SYSTEM (TDAS)

2.1 General Description

This system is designed to evaluate the thermochemical behavior of volatile materials under controlled conditions. As indicated in Figure E-1, it consists of a modular control panel (where the operating parameters for tests are established), several gas cylinders (that supply reaction atmospheres with known compositions), a sample insertion and vaporization chamber, a special quartz tube reactor in a furnace (for the decomposition of samples), a product collection trap, a gas chromatograph, a mass spectrometer, and a minicomputer. Figure E-2 is a block diagram showing a simplified representation of the operational relationships of the various components.

2.2 Operation

In operation, several micrograms of a solid, liquid, or gaseous sample are introduced into a sample insertion chamber (location K in Figure E-1). The chamber is then sealed and flushed with the controlled atmosphere to be used for the experiment. Solid and liquid samples are heated, vaporized at temperatures up to 300°C (over a controlled time interval), and mixed with a continuous stream of the reaction atmosphere. Samples can be flash pyrolyzed or gradually vaporized, depending on the desired reaction conditions. The mixture then passes through a reactor (location M) consisting of an 98-cm long, 0.097-mm inside diameter, thin walled, folded quartz tube enclosed in an electric furnace. The furnace and tube can be operated at temperatures up to 1,150°C. The temperature of the reactor is monitored by a thermocouple located at a point representing the mean temperature for the reactor furnace [1].


O
MODULAR CONTROL PANEL[a]
TEMP. PROG.
L
I
J
H
SAMPLE
G
F
E
D
A
B
C
K
M
N
IN-LINE GC/MS/DS
N_2
(-160°C)

A	HELIUM GAS
B	COMPRESSED AIR
C	INERT CARRIETR
D	PRESSURE REGUALTOR
E	OXYGEN SCRUBBER
F	DIRECTIONAL VALVE
G	FILTER
H	FLOW CONTROL VALVE
I	FLOW TRANSDUCER
J	PRESSURE TRANSDUCER
K	INSERTION CHAMBER
L	TEMPERATURE PROGRAMMER
M	REACTOR IN FURNACE
N	PRODUCT COLLECTION TRAP
O	MODULAR CONTROL PANEL

[a] THE MODULAR CONTROL PANEL DID NOT APPEAR IN THE ORIGINAL PUBLICATION

Figure E-1. Simplified schematic of TDAS [1].

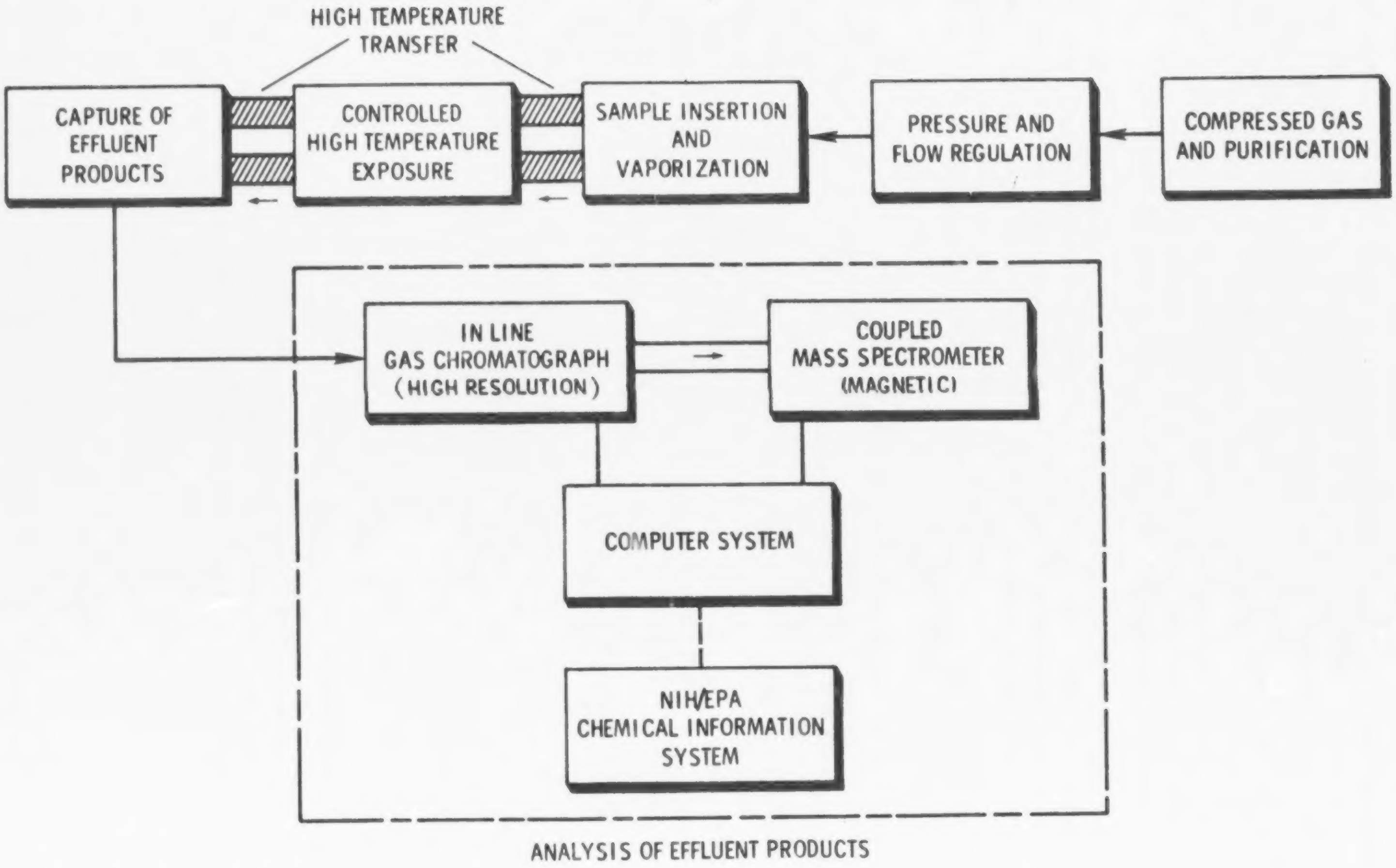

HIGH TEMPERATURE TRANSFER
CAPTURE OF EFFLUENT PRODUCTS
CONTROLLED HIGH TEMPERATURE EXPOSURE
SAMPLE INSERTION AND VAPORIZATION
PRESSURE AND FLOW REGULATION
COMPRESSED GAS AND PURIFICATION
IN LINE GAS CHROMATOGRAPH (HIGH RESOLUTION)
COUPLED MASS SPECTROMETER (MAGNETIC)
COMPUTER SYSTEM
NIH/EPA CHEMICAL INFORMATION SYSTEM
ANALYSIS OF EFFLUENT PRODUCTS

Figure E-2. Block diagram of TDAS [1].

It is estimated that a typical reaction mixture entering the TDAS reactor heats to the reactor temperature within 0.005 second. Ninety-five percent of the molecules are estimated to be exposed to the reported temperature over time intervals with a maximum deviation of 4% to 10% from the reported mean residence time, depending on the conditions of the test. The percent deviation increases as the mean residence time decreases. The temperature is controlled to within ±2°C across the operating range of the device. Mean residence times between 0.25 and 5.0 seconds may be selected [1]. It is possible to operate the reactor at pressures up to two atmospheres.

The effluent from the TDAS reactor enters a sorbent trap (Location N) that can be maintained at -110°C. In the trap, reactions are quenched and reaction products and unreacted sample are collected with a sorbent (usually Tenax-GC, although other materials, such as quartz wool, have also been used). The chemicals collected are then thermally desorbed directly into a capillary column gas chromatograph/mass spectrometer for identification and quantification of reaction products and unreacted sample.

The chromatograph has been used with glass and fused silica capillaries coated with selected materials (such as a 0.1-µm layer of Supelco SP 2100) [2]. The mass spectrometer contains an ion detector upstream of the magnetic sector. This detector may be calibrated and used to measure quantities of pure substances leaving the gas chromatograph at different times. A photomultiplier tube downstream of the magnetic sector of the mass spectrometer responds to the ionic fragments of molecules emerging from the magnetic field. The identity of chemicals and mixtures of chemicals emerging from the gas chromatograph can be determined by comparing the observed ion fragment patterns with those of known compounds. The NIH/EPA Chemical Information Mass Spectral Data Base is routinely used to help identify compounds and mixtures.

Samples of effluent from the reactor may be collected on activated carbon (or other sorbents) simultaneously with the samples collected in the cold sorbent trap described above. These samples could be desorbed with solvents and injected into laboratory gas chromatographs or other analytical devices not directly connected to the TDAS.

3. THERMAL DECOMPOSITION DEVICE (TDD)

3.1 General Description

Figure E-3 is a schematic diagram of the thermal decomposition device (TDD). This device is the predecessor to the TDAS. It consists of a compressed air cylinder (to supply the reaction atmosphere), pressure regulators, flow regulators (to adjust the residence time), a sample insertion and vaporization chamber, a quartz tube reactor in an electrically heated furnace (for the decomposition of samples), a product collection trap, and a flow meter.

3.2 Operation

The TDD is operated in the following manner. Compressed air is filtered (at location C in Figure E-3) and its flow rate is adjusted (location D) to provide the desired residence time. The gas enters the inlet chamber (location G)

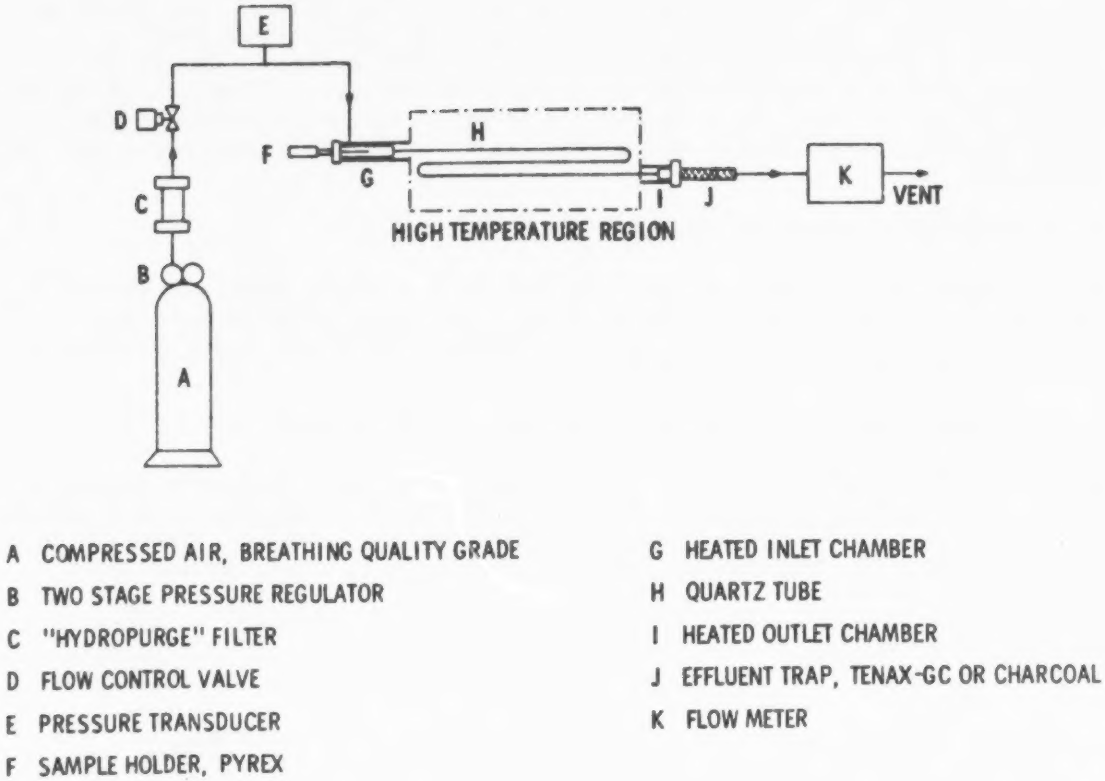

E
D
F
H
G
C
I
J
K
VENT
HIGH TEMPERATURE REGION
B
A
A COMPRESSED AIR, BREATHING QUALITY GRADE
B TWO STAGE PRESSURE REGULATOR
C "HYDROPURGE" FILTER
D FLOW CONTROL VALVE
E PRESSURE TRANSDUCER
F SAMPLE HOLDER, PYREX
G HEATED INLET CHAMBER
H QUARTZ TUBE
I HEATED OUTLET CHAMBER
J EFFLUENT TRAP, TENAX-GC OR CHARCOAL
K FLOW METER

Figure E-3. Schematic of thermal decomposition device [3].

which surrounds a sample holder containing several micrograms of sample (location F). The chamber is gradually heated to a maximum temperature of about 300°C to vaporize the sample [3]. As material from the sample vaporizes, it is swept into the reactor chamber (location H) by the compressed air flow. In the reactor chamber, the reaction mixture is thermally stressed at a controlled temperature (up to 1,000°C). An 84-cm by 0.8-mm ID quartz reaction chamber and an 84-cm by 2.14-mm ID quartz reaction chamber are available. The average temperature of the reactor furnace is controlled to ±5°C; but there are temperature gradients in the furnace of up to 50°C, compared to the reported average temperature. In most experiments, the residence times in the reactor were approximately one second (±0.04 s), but residence times between 0.5 s and 3.0 s are possible [3].

After the mixture passes through the reactor, it is cooled to approximately 300°C [3]. The partially cooled mixture then enters the effluent trap (location J), where it rapidly cools to ambient temperature. The effluent trap and sorbent (Tenax GC or charcoal) collect unreacted sample and the products of decomposition of the waste. The sorbents used at room temperature are generally suitable for materials with molecular weights between 78 and 800.

At the end of a run, the effluent trap is removed from the TDD. If Tenax is the sorbent, the trap is inserted directly into an adapter on a separate laboratory gas chromatograph (GC). The trap is then heated to desorb the products, which are flushed into the GC by a carrier gas. If activated carbon is used as the sorbent, the products are desorbed with a suitable solvent. A sample of the solvent/product mix is then injected directly into the GC for analysis.

4. DIFFERENCES BETWEEN THE TDAS AND TDD

Both of these devices were designed for the purpose of studying the thermal chemical decomposition of various materials, and their basic designs and methods of operation are quite similar. However, important specifications, summarized in Table E-1, are different.

5. DIFFERENCES BETWEEN INCINERATORS AND LABORATORY DEVICES

While the results obtained with the previously described laboratory devices may resemble the performance of an incinerator, there are differences. The laboratory devices are not designed to simulate incinerator behavior. They are designed to generate basic thermal decomposition data at the molecular level.

The operating conditions in most incinerators are not as simple as those in the laboratory devices. Among the potential complications associated with real incinerators (compared to the TDAS and TDD systems) are the following:

- Wastes may enter the combustion chamber of an incinerator as liquids or solids, while only gases enter the reaction zones in the TDAS and TDD.
- Direct combustion of fuel and/or waste supplies the heat required for the reactions in incinerators, and the waste in an incinerator may pass directly through a distinct flame or flame front. The TDAS and TDD are indirectly heated.
- There may be a significant lack of homogeneity in the temperature profiles of incinerators, and the temperature is often not as closely controlled as in the laboratory devices. Furthermore, the maximum temperature in an incinerator may be higher than the highest temperature at which laboratory devices can be operated.
- The residence times reported for incinerators often does not really represent the exposure times of wastes at the reported operating temperatures. An "upper bound" residence time is the only value reported for many incinerators. This represents the total volume of the incinerator combustion chamber (whether or not it is all at the reported temperature) divided by the volume rate of flow of flue gas out of the chamber. All of the waste passing through an incinerator does not have the same residence time. Some waste passes through faster than other portions of the same charge, resulting in a residence time distribution. The mean residence times in the previously described laboratory devices are well controlled and represent true residence times for all of the

TABLE E-1. COMPARISON OF THE TDD AND TDAS

Parameter	TDD [3]	TDAS [1]
Sample type	Liquid or soluble solids with low volatility and molecular weights between 78 and 800.	Gas, liquid or solid samples with molecular weights less than about 800.
Reactor construction	Heavy-wall folded quartz 84 cm long, 0.8-mm ID (an 84. cm long, 2.14-mm ID tube is also available)	Thin-wall folded quartz (98 cm long, 0.97 mm ID)
Regulation of mean reactor temperature	±5°C	±2°C
Maximum operating temperatures	1,000°C[a]	1,150°C[b]
Range of temperatures in reactor	+25°C -50°C	±2°C
Residence time range	0.5 - 3.0 s[c]	0.25 - 5.0 s
Effluent traps	Ambient temperature trap	Cryogenically cooled trap
Sampling and analysis	Sample must be manually removed from unit for analysis on a nearby GC	Sample normally thermally desorbed in-situ and carried directly to GC/MS by the carrier gas.

[a] Limited by the heating unit.

[b] Limited by the properties of quartz.

[c] Personal communication with W. A. Rubey, 8 August 1980.

waste passing through the devices at the reported temperatures with a degree of accuracy seldom (if ever) achieved for incinerators.

- Physical and chemical interactions between components of mixtures of wastes and reaction products (such as adsorption on particulates and catalysis) might inhibit or accelerate the rate of waste decomposition and combustion product formation. Furthermore, interaction of the combustion products with the walls of the incinerator might affect the degree of combustion and the products. Possible wall effects include heat transfer, flame quenching, the adsorption of reactive components on surfaces, and catalysis. Some of these effects cannot be studied in the TDAS and TDD laboratory units, since solids and liquids cannot enter the reaction chambers of those devices and the walls are not the same as in incinerators.

- Mixing in an incinerator will be different from mixing in laboratory devices. This can result in changes in the relative proportions of uncombusted, partially combusted, and completely combusted waste.
- In an incinerator, the conditions to which various molecules are exposed can vary greatly in terms of temperature, oxygen concentration, and concentrations of free radicals.
- The laboratory devices were usually operated in such a manner that waste concentrations were very low, and the amounts of oxygen leaving the reactors were not significantly different from the amounts going into the reactors. Furthermore, most experiments were performed with 21% oxygen (although 0% to 40% oxygen have also been used). The oxygen concentrations found in incinerator flue gas are often much lower than the oxygen concentrations used in laboratory experiments.
- The feed rate of incinerators may be constant, allowing steady state conditions to occur. The laboratory devices are batch fed.

6. POSSIBLE APPLICATIONS OF LABORATORY EXPERIMENTS

The previously described laboratory devices were not designed to simulate incinerators, and no systematic studies of the performance of the TDAS or TDD compared to incinerators of different sizes, designs, and operating conditions have been reported. Furthermore, no systematic studies of the quantitative limitations of scaleup methods are available. As a result, great caution must be exercised when using data from the laboratory device when designing trial burn studies, since the applicability of the data to predicting the behavior of hazardous waste incinerators has not been demonstrated. However, some potential uses for laboratory experiments exist:

- The rate constant for the decomposition of a waste and its temperature dependence can be identified with the TDAS and the TDD [4].
- The TDAS and TDD devices can be used to identify byproducts of decomposition of hazardous materials and the conditions under which they are formed.
- Experienced combustion chemists and engineers can obtain evidence that can aid in understanding the detailed operating conditions within an incinerator by comparing the results of laboratory decomposition experiments to the results of full-scale test burn experiments under similar conditions.
- Various thermochemical modeling techniques used to predict the behavior of full-scale incinerators can be tested using data from laboratory experiments. Once their accuracy for predicting the behavior of waste in

relatively well controlled circumstances is determined, the models can be tested in experiments on incinerators. Most of these models use an activation energy for the reactive species. An apparent activation energy for the reaction of a dilute waste with oxygen can be derived with TDAS or TDD laboratory data [4].

- Data from laboratory experiments can be compiled and used to help develop empirical modeling techniques for full-scale incinerators by simulating (insofar as possible) various microscale regions within an incinerator in laboratory experiments and then using the data to help predict what happens to waste after it passes through such regions in incinerators.
- Data from the device can be used to help determine research priorities for hazardous waste incineration (when pilot or full-scale trial burn data are unavailable) by considering the types, amounts, and potencies of the reaction products observed.
- Data from laboratory waste decomposition experiments can help to determine operating conditions at the beginning of trial burns. Temperature, retention time, turbulence, and excess air levels at the beginning of trial burns should be far enough above those associated with unacceptable emissions (based on laboratory data) to give a reasonable confidence of having acceptable emissions. The margins of safety for this purpose have not been systematically studied.
- Data from laboratory tests can be used to help determine which compounds to monitor during trial burns and at full-scale industrial installations.

Figure E-4 shows the effects of oxygen concentrations on the thermal decomposition of a PCB in the thermal decomposition device. The high sensitivity to oxygen is clearly shown. This suggests that operating laboratory devices (or modifying them to operate) with amounts of excess air similar to those found in an incinerator may significantly improve the utility of the data generated. If the percent oxygen used in a laboratory experiment is equivalent to the percent oxygen in incinerator flue gas, the probability of a laboratory experiment yielding a lower destruction and removal efficiency than that achieved in an incinerator will be increased (compared to operation of a laboratory device at 21% oxygen). This can increase the utility of laboratory data for quickly making conservative estimates of acceptable operating conditions at the beginning of trial burns.

7. RESULTS OF LABORATORY-SCALE DECOMPOSITION EXPERIMENTS

7.1 Kepone Results

Kepone decomposition experiments were performed in the thermal decomposition device. As can be seen from Table E-2, the destruction of Kepone increases rapidly with increasing temperature above 400°C (at a relatively constant retention time). It is also apparent that there are several byproducts: hexachlorobenzene, hexachlorocyclopentadiene [3] and hexachloroindenone. The amounts of byproducts formed are dependent upon the reactor temperature. This information is graphically represented in Figure E-5.

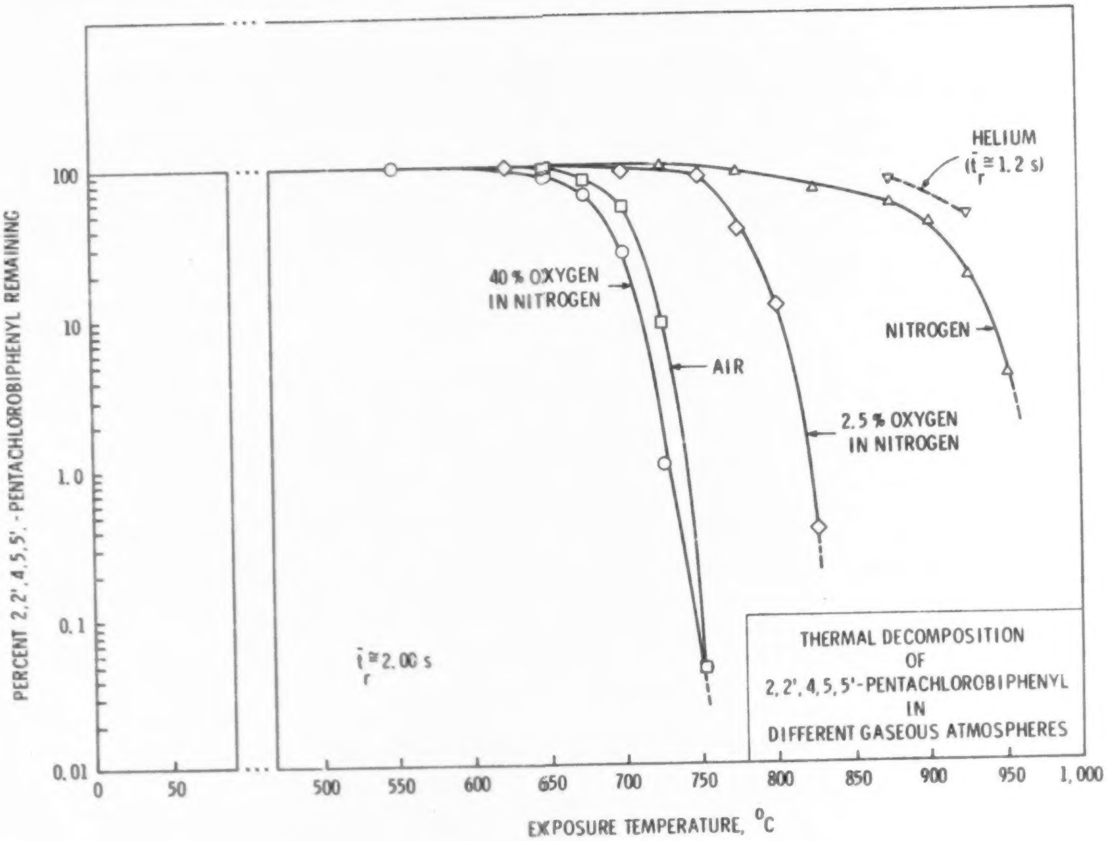


Figure E-4. Effect of oxygen concentration [5].

TABLE E-2. KEPONE THERMAL DESTRUCTION SUMMARY [3[a]]

Waste: kepone; sample size: 40 μg;
laboratory device: thermal decomposition device.

Unit temperature, °C	Input atmosphere	Retention time, s	Destruction and removal efficiency, %	Byproducts identified[b]	Relative quantity of byproducts[c]
302	Air, 21% O_2	0.93	0	None	None
397	Air, 21% O_2	0.99	12	Hexachlorocyclopentadiene	0.05
				Hexachloroindenone[a]	0.05
435	Air, 21% O_2	0.94	48	Hexachlorocyclopentadiene	0.5
				Hexachloroindenone	0.75
463	Air, 21% O_2	0.93	96	Hexachlorocyclopentadiene	0.85
				Hexachloroindenone	0.65
495	Air, 21% O_2	1.10	≥99.55	Hexachlorocyclopentadiene	0.65
				Hexachloroindenone	1.2
				Hexachlorobenzene	-[d]
603	Air, 21% O_2	0.99	≥99.55	Hexachlorobenzene	0.04
				Hexachloroindenone	1.75
				Hexachlorocyclopentadiene	0.05
708	Air, 21% O_2	0.91	≥99.55	Hexachlorobenzene	1.10
				Hexachloroindenone	0.05
807	Air, 21% O_2	0.92	≥99.55	Hexachlorobenzene	0.45
910	Air, 21% O_2	0.94	≥99.999655[e]	Hexachlorobenzene[e]	0.15
433	Air, 21% O_2	0.23	6	Not reported	NA[f]
433	Air, 21% O_2	1.04	53	Not reported	NA
433	Air, 21% O_2	1.79	68	Not reported	NA

[a] Hexachloroindenone identified in a personal communication with Don Duvall and Wayne Rubey, 4 August 1980.

[b] Byproducts collected on Tenax GC and detected in quantifiable amounts unless otherwise specified.

[c] Reported as relative peak heights on a flame ionization detector.

[d] Detected, but below measureable levels.

[e] Collected on activated carbon, desorbed with mixed solvent (acetone, benzene, CS_2) and quantified with an electron capture detector (residual Kepone 138 pg; hexachlorobenzene ~200 nanograms).

[f] Not applicable.

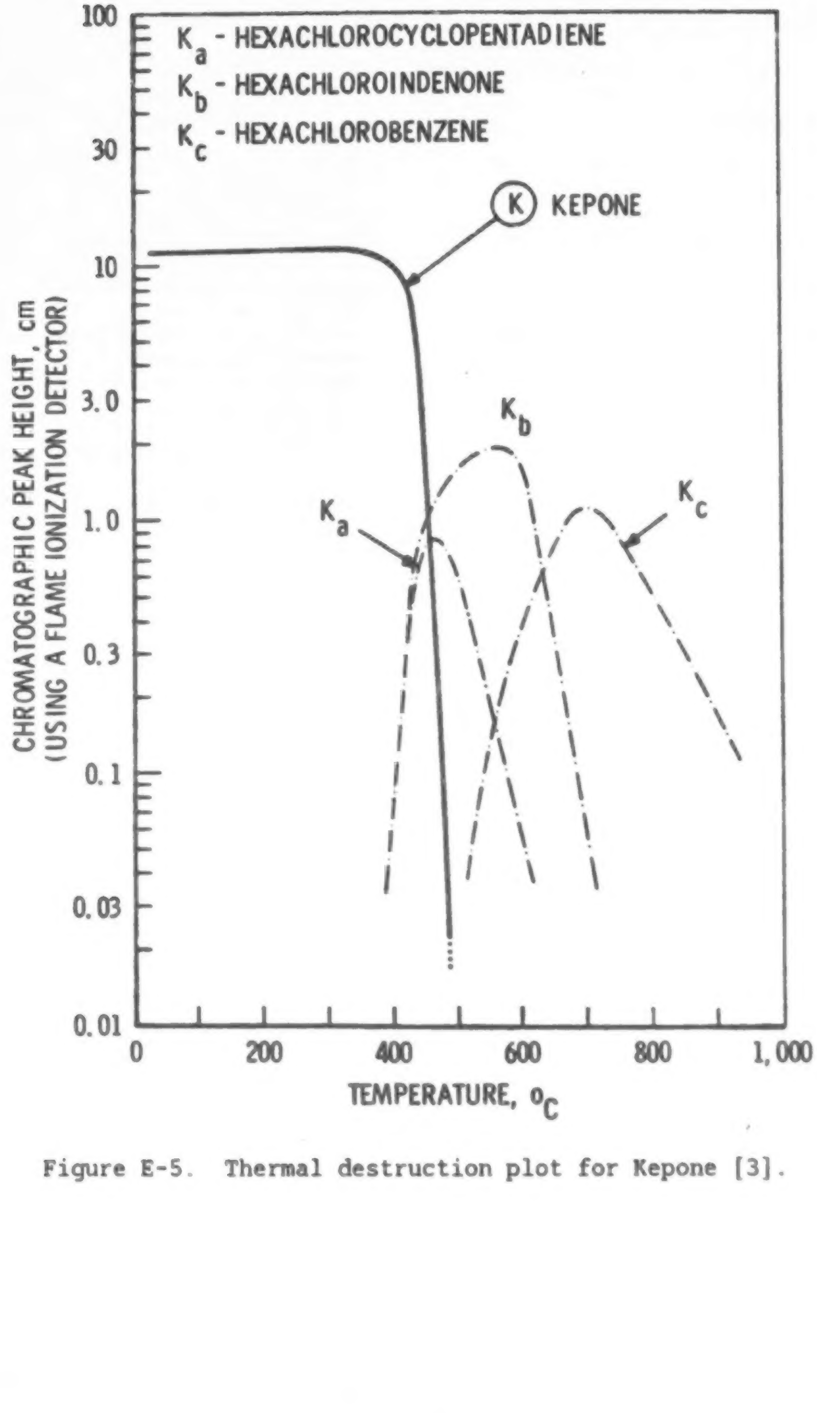


Figure E-5. Thermal destruction plot for Kepone [3].

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3. Duvall, D. S.; and Rubey, W. A. Laboratory evaluation of high temperature destruction of Kepone and related pesticides. Cincinnati, OH; U.S. Environmental Protection Agency; 1976 December. 59 p. EPA-600/2-76-299.

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APPENDIX F

TRIAL BURN SUMMARIES

TABLE F-1. TRIAL BURN SUMMARIES

Waste	Incinerator	Temperature (°F)	Temperature (°C)	Residence[d] time[d], s	Percent excess air	Combustion efficiency	Destruction efficiency[a]	Destruction and removal efficiency[b]	HCl scrubber efficiency	Reference
Aldrin, Shell (20% aldrin granules)	Multiple chamber	1580-2100	860-1150	P 1.4-3.2 S 1.4-3.6	48-155	NR[c]	Aldrin >99.99 Total species >99.99			1
Aldrite®, Shell 4 aldrin (41.2% emulsifiable concentrate)	Multiple chamber	1120-2080	600-1140	P 1.2-6.9 S 7.6-1.2	70-380	NR	Aldrin >99.99 Total species >99.99			1
Atrazine (liquid Aatrex® 4L herbicide)	Multiple chamber	1030-1900	550-1040	P 1.6-7.8 S 1.3-6.9	52-143	NR	>99.99			1
Atrazine (solid Aatrex® 80W herbicide)	Multiple chamber	1120-1960	600-1070	P 2.2-6.8 S 2.8-6.4	43-146	NR	Atrazine >99.99 Total species >99.99			1
Para-arsanilic acid	Molten salt combustion	1695	924	NR	NR	NR	>99.999			2
Captan solid (Ortho Orthcide® 50 wettable)	Multiple chamber	1200-1850	650-1010	P 1.8-6.8 S 1.8-6.5	76-252	NR	Captan >99.99 Total species >99.99			1
Chlorodane (5% chlorodane dust 95% inert ingredients)	Liquid injection	1685-2030	918-1110	0.132-0.452	NR	NR	Chorodane >99.99			3
Chlorodane (72% emulsifiable concentrate and No.2 fuel oil)	Liquid injection	1780-2005	971-1096	0.140-0.267	45-47.3	NR	Chlorodane >99.999			3
Chlorinated aliphatics (28% methylene-chloride, 2% trichloro-ethylene, 70% m-propanol)	Cement kiln	2552-2642	1400-1450	NR	NR		Trichloro-ethylene 99.9998 Methylene chloride 99.995			4

(continued)

TABLE F-1 (continued)

Waste	Incinerator	Temperature (F)	Temperature (°C)	Residence time^d, s	Percent excess air	Combustion efficiency	Destruction efficiency^a	Destruction and removal efficiency^b	HCl scrubber efficiency	Reference
Chloroform	Molten salt combustion	1504	818	NR	NR	NR	>99.999			2
DDT (5% oil solution)	Liquid injection	1540->2300	878->1260	0.16-1.30	26-70	NR	>99.99			3
DDT (DDT powder, 75% active ingredients)	Municipal multiple hearth sludge incinerator	Trial 1 1107-2337 2 1191-2417 3 1011-2120 4 1450-2822	Trial 1 597-1225 2 644-1325 3 544-1160 4 788-1550	NR	6.5-10.0	NR	Trial 1 99.970 2 99.975 3 99.977 4 99.983			5
DDT (10% DDT, dust 90% inert ingredients)	Multiple chamber	1710-2210	930-1210	P 1.3-2.4 S 1.2-2.5	58-164	NR	DDT >99.99 Total species >99.98			1
DDT (20% DDT, 80% aromatic petroleum derivative solvent)	Liquid injection	1730-2000	943-1093	0.139-0.593	42-47	NR	>99.98			3
DDT (25% emulsifiable concentrate, 72% aromatic petroleum derivative, and 3% inert ingredients)	Liquid injection	1590-1980	865-1082	0.136-0.727	42-65	NR	>99.9			3
DDT (25% emulsifiable concentrate, 18% petroleum oil, 55% xylene, 2% inert ingredients)	Multiple chamber	1700-2180	930-1180	P 0.9-3.0 S 0.7-3.2	64-166	NR	DDT >99.98->99.99 Total species >99.98->99.99			1
DDT oil (20% emulsified DDT waste oil, 1.7% PCB)	Thermal oxidizer waste	Trial 1 1600	871	NR	169	NR	DDT NA PCB 99.970			6
		2 1600	871	3.36	157	NR	DDT 99.9999 PCB 99.9995			
		3 1600	871	2.94	163	NR	DDT 99.999 PCB 99.9921			
		4 1800	982	3.03	123	NR	DDT 99.9999 PCB 99.9941			
		5 1800	982	3.96	123	NR	DDT 99.9999 PCB 99.9951			

(continued)

TABLE F-1 (continued)

Waste	Incinerator	Temperature (F)	Temperature (°C)	Residence time^d, s	Percent excess air	Combustion efficiency	Destruction efficiency^a	Destruction and removal efficiency^b	HCl scrubber efficiency	Reference
DDT power	Molten salt combustion	1652	900	NR	NR	NR	99.998			2
Dieldrin (15% emulsifiable concentrate and 72% chlorodane emulsifiable concentrates. Mixed 1:3 ratio)	Liquid injection	1610-1900	877-1038	0.153-1.171	45.8-51	NR	>99.98			3
Diphenylamine-HCL	Molten salt combustion	1692	922	NR	NR	NR	>99.999			2
Ethylene manufacturing waste (benzene 20%, toluene 20%, cyclohexadiene 20%, styrene 20%, indene 5%, xylene 2%, napthalene 3%)	Liquid injection	2460-3186	1349-1752	0.14-0.19	NR	NR	Total organics 99.95-99.96 "waste" constituents 99.9999			7
GB ($C_4H_{10}O_2PF$) chemical warfare agent	Molten salt combustion	1652-1832	900-1000	NR	NR	NR	Trial 1 99.99999969 2 99.99999976			2
Herbicide orange	Two identical refractory lined furnaces on board the M.T. Vulcanus while at sea	Average wall 2323 Average flame 2732	Average wall 1273 Average flame 1500	1.0	45-144	>99.98	2,4-D >99.9 2,4,5-T >99.9 Total hydrocarbon 99.982-99.992 Herbicide orange >99.999 TCDD >99.93->99.99 Chlorinated hydrocarbons, >99.999			
Hexachlorocyclopentadiene	Liquid injection	2458-2512	1348-1378	0.17-0.18		NR	Total organics 94-99.95 Waste constituents >99.999			2

(continued)

TABLE F-1 (continued)

Waste	Incinerator	Temperature (F)	Temperature (°C)	Residence time^d, s	Percent excess air	Combustion efficiency	Destruction efficiency^a	Destruction and removal efficiency^b	HCl scrubber efficiency	Reference
Kepone (in acetic acid)	After burner	1999-2300	1093-1260	2.15-2.44	3.75-4.8		99.98	>99.9999		9
Kepone (in Toledo sludge)	Rotary kiln pyrolyzer with afterburner	1900-2000	1038-1093	2.06-2.26	NR	NR		>99.9999		9
Lindane (12% emulsifiable concentrate 71% aromatic petroleum, 12% xylene, 5% emulsifier)	Liquid injection	1910-2310	1043-1265	0.132-1.177	31-50	NR	>99.999			3
Malathion (dissolved in xylene)	Molten salt combustion	1652	900	NR	NR	NR	99.9999-99.9998			2
Malathion (25% wettable 75% inert ingredients)	Multiple chamber	1170-1900	630-1040	P 1.9-5.7 S 1.8-5.6	43-157	NR	Malathion >99.99 Total species >99.99			1
Malathion (57% emulsifiable concentrate 33.09% aromatic petroleum, 9.91% inert ingredients)	Multiple chamber	1110-1980	600-1080	P 2.2-6.8 S 2.2-6.5	44-311		Malathion >99.99 Total species >99.99			1
Methyl methacrylate (MMA) waste in 38% water	Fluidized bed	1425-1450 1515-1549	Bed average 774-788 Free board average 820-843	12	11.6-13.4	NR	Total organics 99.96-99.98 Constituents >9.999			7
0.3% Mirex bait on corncob grit	Multiple chamber	1090-1780	590-940	P 1.7-6.0 S 1.5-6.2	57-225	NR	>98.21-99.98 Total species >97.78-99.96			1
Mustard (chemical warfare agent)	Molten salt combustion	1652-1832	900-1000	NR	NR	NR	>99.999985 >99.999982			2

(continued)

TABLE F-1 (continued)

Waste	Incinerator	Temperature (°F)	Temperature (°C)	Residence time^d, s	Percent excess air	Combustion efficiency	Destruction efficiency^a	Destruction and removal efficiency^b	HCl scrubber efficiency	Reference
Nitrochlorobenzene (95% nitrochlorobenzene, 5% dinitrochlorobenzene	Liquid injection	Afterburner 2385-2430	1307-1332	2.3	NR	NR	Total organics 99.84-99.87 Constituents >99.999- >99.99		99.8	7
Nitroethane	Molten salt combustion	1638	892	NR	NR	NR	>99.993			2
Phenol Waste sludge (86% water)	Fluidized bed	Bed average 1364-1394 Free board average 1495-1650	 740-754 813-899	12-14	10.7-12.6	NR	Total organics 99.93-99.95 Constituents >99.99			7
Picloram Liquid (24.9 Picloram, 75.1% inert ingredients)	Multiple chamber	986-1886	530-1030	P 1.2-7.6 S 1.2-8.0	50-298	>99.99	Picloram >99.99 Total species >99.63- >99.99			1
Picloram Tordon 10K pellets	Multiple chamber	1190-1870	640-1020	P 1.3-6.7 S 1.4-7.4	72-227	NR	Picloram >99.99 Total species >99.93 (approx.)			1
PCBs (3756 Arochlor 1241/1 mixed with 2/oil)	Rotary kiln with a modified burner	Kiln average 1359-1600 Afterburner 2304-2410 Hot duct average 2152-2167	 737-871 1262-1321 1178-1186	2.63-2.74	NR	99.995- 99.999	99.999968- 99.999977			10
PCB Capacitors	Rotary kiln liquid injection burner, afterburner	Kiln 2286-2442 Afterburner 2428-2430	 1252-1339 1331-1332	3.0-3.2	NR	NR	Total organics >99.98-99.96 Constituents >99.9999-99.5		99.8	11
PCB (375 g PCB mixed with 1242 liters of #2 oil)	Cement Kiln	2552-2642	1400-1450	NR	NR	NR	>99.9998			4
Polyvinyl chloride waste sludge (72% water, 28% solids)	Rotary kiln with afterburner	1st zone 1600 2nd zone 1800-2000	1st zone 870 2nd zone 980-1090	3	75-140	NR	Total organics 99.80-99.88 Chlorinated organics 99.99		12	
Toxaphene (20% toxaphene dust, 80% inert ingredients)	Multiple chamber	1240-1880	670-1030	2.4-7.7 2.8-8.3	44-166		99.99			1

(continued)

TABLE F-1 (continued)

Waste	Incinerator	Temperature (°F)	Temperature (°C)	Residence time[d], s	Percent excess air	Combustion efficiency	Destruction efficiency[a]	Destruction and removal efficiency[b]	HCl scrubber efficiency	Reference
Toxaphene (60% emulsifiable concentrate)	Multiple chamber	Primary 1150-1900	Primary 620-1040	2.2-6.7 2.2-6.5	47-349	NR	99.99			1
Trichloroethane	Molten salt combustion	1544	840	NR	NR	NR	>99.999			2
2,4-D Low volatile liquid ester (94.8% isoctyl ester 082,4-5D)	Liquid injection	1365-1660	741-904	0.199-0.915	46.8-53.2	NR	>99.89			3
2,4,5-T Weedon TM (20% active ingredient)	Municipal multiple hearth sewage sludge incinerator	855-1725	457-940	NR	6-10	NR	99.980- 99.996			5
2,4,5-T Herbicide (in isopropanol)	Single hearth furnace with afterburner	1742	950	2-3	NR	NR	99.995			13-14
2,4,5-T Herbicide (in wood chips)	Single hearth furnace with afterburner	932-1562	500-850	0.6-0.7	NR	NR	99.995			13-14
2,4,5-T Herbicide (in wood chips and dry leaves)	Single hearth furnace with afterburner	212	100	1.0	NR	NR	92			13-14
VX ($C_{11}H_{26}O_2PSN$) (Chemical warfare agent)	Molten salt combustion	1652-1832	900-1000	NR	NR	NR	>99.9999945- 99.999989			2
Zineb (75% wettable powder Fungicide (25% inert ingedients)	Multiple chamber	1310-1832	710-1000	1.8-5.2 1.7-5.1	62-165	NR	>99.99			1

[a] $$DE = \frac{W_{in} - W_{out}}{W_n} \times 100$$

where: W_{in} = mass feed rate of the principal toxic component

W_{out} = mass emission rate of the principle toxic component leaving incinerator combustion zone (upstream of all pollution control equipment)).

[b] $$DRE = \frac{W_{in} - W_{out}}{W_{in}} \times 100$$

where: W_{in} = mass feed rate of the principal toxic component

W_{out} = mass emission rate of the principal toxic component in the stack (after all pollution control devices)

[c] NR - No reported.

[d] P - Primary chamber

S - Secondary chamber

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